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MONTEREY, CALIFORNIA

Digital Array Radar for Ballistic Missile Defense and Counter-Stealth Systems Analysis and Parameter Tradeoff Study

by

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14 September 2006

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13. ABSTRACT

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Our completed research defined the operational and technical requirements for the system, called the Digital Array Radar for BMD and Counter-stealth (DARBC). Initial analysis included characterization of the threat and definition of the Concept of Operations (CONOPS). Basic operational Key Performance Parameters (KPPs) were defined. Based on a notional ballistic missile Radar Cross Section (RCS), a radar technical parameters study derived the technical requirements for the radar necessary to meet the KPPs. Related research topics included radar parameter sensitivity, cooling, search pattern options, Electronic Attack (EA), ship flexure, topside array layout, supportability, and cost. Finally, reaction time modeling was conducted to quantify the increase in search volume and decision making time using the DARBC.

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Our research defined the operational and technical requirements for the system, called the Digital Array Radar for BMD and Counter-stealth (DARBC). Initial analysis included characterization of the threat and definition of the Concept of Operations (CONOPS). Basic operational Key Performance Parameters (KPPs) were defined. Based on a notional ballistic missile Radar Cross Section (RCS), a radar technical parameters study derived the technical requirements for the radar necessary to meet the KPPs. Related research topics included radar parameter sensitivity, cooling, search pattern options, Electronic Attack (EA), ship flexure, topside array layout, supportability, and cost. Finally, reaction time modeling was conducted to quantify the increase in search volume and decision making time using the DARBC.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS

Acronym	Definition
Ao	Operational Availability
AD	Air Defense
ASCM	Anti-Ship Cruise Missile
BMD	Ballistic Missile Defense
CAS	Computer Algebra System
CDD	Capability Development Document
CONOPS	Concept of Operations
CONUS	Continental United States
COTS	Commercial Off The Shelf
DARBC	Digital Array Radar for BMD and Counter-Stealth
DDS	Direct Digital Synthesizer
DIRM	Design Interface Risk Matrix
DoD	Department of Defense
DOF	Degree Of Freedom
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities
EA	Electronic Attack
ECM	Electronic Counter Measure
EMP	Electromagnetic Pulses
ESM	Electronic Surveillance Measures (System)
ETG	Electronic Target Generator
EW	Electronic Warfare
FDFI	Fault Detection Fault Isolation
FMS	Foreign Military Sales
GaAs	Gallium Arsenide
GPS	Global Positioning System
HEL	High Energy Laser
ICBM	Inter-Continental Ballistic Missile
ICD	Initial Capabilities Document
IO	Information Operations
IR	Infra-Red
IRBM	Intermediate Range Ballistic Missile
JBMC2	Joint Battle Management Command and Control
KEI	Kinetic Energy Interceptor
KPP	Key Performance Parameters
LCC	Life Cycle Cost
LNA	Low Noise Amplifier
LOS	Line of Sight
MDA	Missile Defense Agency
MHz	Megahertz

MIC	Miniature Integrated Chip
MMIC	Micro Miniature Integrated Chip
MRBM	Medium Range Ballistic Missile
MSSE	Master of Science Systems Engineering
MTBF	Mean Time Before Failure
MTTR	Mean Time To Repair
NATO	North American Treaty Organization
NAVICP	Navy Inventory Control Point
NAVSEA	Naval Sea Systems Command
NNEMP	Non-Nuclear Electro-Magnetic Pulse
NPS	Naval Postgraduate School
NSWC PHD	Naval Surface Warfare Center Port Hueneme Division
NTSP	Navy Training System Plan
OA	Opportunistic Array
OASR	Opportunistic Array Surveillance Radar
OEM	Original Equipment Manufacturer
OV	Operational View
P_D	Probability of Detection
PFA	Probability of False Alarm
QRS	Quartz Rate Sensor
RCS	Radar Cross Section
RM&A	Reliability, Maintainability, Availability
RV	Re-entry Vehicle
SATCOM	Satellite Communication
SE	Support Equipment
SEP	Systems Engineering Plan
SESEF	Shipboard Electronic Systems Evaluation Facility
SLBM	Submarine Launched Ballistic Missile
SM-3	Standard Missile - 3
S/N	Signal to Noise Ratio
SNR	Signal to Noise Ratio
SRBM	Short Range Ballistic Missile
TBM	Theater Ballistic Missile
TEL	Transportable Erectable Launchers
TEMP	Test and Evaluation Master Plan
T/R	Transmit-Receive
UNREP	Underway Replenishment
USAF	United States Air Force
UHF	Ultra High Frequency
URMTT	Universal Radar Moving Target Transponder
USN	United States Navy
VHF	Very High Frequency
WCS	Weapon Control Sensor
WMD	Weapons of Mass Destruction

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EXECUTIVE SUMMARY

The purpose of this Capstone project was to perform a detailed system analysis for a Very High Frequency (VHF) / Ultra High Frequency (UHF) Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-Stealth (DARBC). Results of this analysis have been recorded in an Initial Capabilities Document (ICD)[1] and Capabilities Design Document (CDD)[2].

United States Navy (USN) sources indicate a need for long-range (order of thousands of kilometers) shipboard radar for BMD to augment and expand current capabilities to defend against the increasing ballistic missile threat. The Naval Postgraduate School (NPS) is conducting radar architecture research based on an Opportunistic Array (OA) and is assessing the needed critical technologies to be incorporated into a ship-wide digital phased array radar.[3] An OA radar is an integrated, ship-wide, digital, phased-array radar, in which antenna elements are placed at available open areas over the entire ship's length. The DARBC has the potential to fulfill the U.S. Navy's BMD sensor missions, including long-range search, detection, track and preliminary discrimination of exo-atmospheric ballistic missiles. The increase in maximum detection range over existing ground-based and shipboard sensors would provide a mobile early warning capability that can improve engagement by extending the time available for engagement decision making and providing earlier track information for designation to other engagement sensors. This increases opportunities to engage and re-engage targets, increasing the overall Probability of kill (P_k). This long-range search capability would decrease the workload of existing BMD capable Aegis platforms so that those systems could focus on the closer range Air Defense (AD) mission.

This research first investigated the expected threats and Concept of Operations (CONOPS) for employment of an OA radar configured ship. Threat Radar Cross Section (RCS) assumptions were developed providing a common basis for Probability of Detection (P_D) calculations for a notional S-band radar and the DARBC radar. Determination of the Key Performance Parameters (KPPs) of the OA radar was

developed based on the CONOPS and P_D capabilities in order to develop an ICD[1] and CDD[2]. Additional research included analysis of other radar performance parameters including antenna gain, Transmit/Receive (T/R) element and total array power, number of pulses integrated, antenna integration efficiency, receiver noise bandwidth, receiver noise figure, probability of false alarm, and radar transmit frequency. Sensitivity analysis was conducted on all of the radar technical parameters but primarily focused on improving performance of the DARBC. This sensitivity analysis further characterized the impacts of total power, antenna gain, and number of T/R elements as they relate to P_D. Analysis of the radar was based on achieving a KPP for a 0.90 P_D at a maximum range that will support cue to the S-band radar. This "Handoff Range" for cue to track a ballistic missile target was calculated to be a range of 748 km. This is the range where the S-band radar has a P_D of 0.5 for a notional ballistic missile RCS. A Waterloo Maple 7 ® software model based on the radar range equation was used to evaluate radar parameters and perform sensitivity analysis. Microsoft Excel ® and MATLAB ® models were developed to examine RCS as a function of aspect angle and radar frequency. These models were used to refine assumptions for P_D in order to determine handoff range for KPP finalization.

Current S-band radars used by the US Navy to search for ballistic missiles consume many resources performing long-range search functions, reducing their performance level in the closer-range Air Defense (AD) mission. Also, the S-band radars are actually capable of tracking targets at ranges greater than their maximum instrumented search range. The DARBC will provide a benefit to current S-band radar systems. It will provide a longer-range search capability allowing the S-band radar to acquire the target at a range that would have been outside the acquisition range for the S-band radar if operating alone. A timeline analysis was conducted to estimate the additional reaction time provided to the S-band ship and subsequent ability to engage and re-engage a ballistic missile threat. The DARBC concept has not defined the complete mission, associated capabilities, or systems the ship would support. The ship could additionally support engagement of ballistic missiles with Standard Missile 3 (SM-3) or other future weapons such as a sea-launched version of the Kinetic Energy Interceptor

(KEI) missile or High Energy Laser (HEL). Scenarios were developed as part of the CONOPS for cases where the DARBC ship would cue a fire control sensor (such as the S-band radar system described above) on the DARBC ship or other platform. Models built using Microsoft Excel ®, and Arena ®, were used to perform timeline analysis determining the time advantage provided.

Radar design parameters and other considerations were examined for a few areas that were considered key to the planned capabilities of the radar. These were used for the development of an ICD[1] and CDD[2] including operational requirements and performance requirements. These areas included cooling requirements of T/R elements, search pattern capabilities, and array density and topside integration concepts. As the radar has considerable transmitting power, capability to support Electronic Attack (EA) was studied for missions of jamming, deception, and destruction of threat key electronic components. Supportability of the radar was examined to consider maintenance requirements for such a new radar design concept. Supportability and design risk items were documented and assessed for relative risk levels for an eventual DARBC acquisition program. Radar errors due to ship flexure were researched to estimate error budget contributions of flexure and other key errors such as time latency and geolocation to a sensor located away from the DARBC ship. Previous ship development program test results were used as a basis of ship flexure assumptions and development of the error budget. BMD mission considerations for the evolving threat, including increased ranges for engagement, have the potential to require increased accuracies on radar systems. Dynamic compensation methods of ship flexure were examined for application in the DARBC.

This document was prepared by the Radar group (Team “R”) of the Naval Postgraduate School Masters of Science in Systems Engineering (MSSE) program, Naval Surface Warfare Center (NSWC) Port Hueneme Division Cohort #4. It focuses only on the radar as a sensor and a weapon, not addressing potential communication capabilities. This research concluded that the OA concept as defined by the DARBC operational and technical requirements has the potential of providing a very real and significant benefit to the USN and BMD program. Further research is recommended in a of areas of modeling

of the radar, ship integration, operational requirements identification, and Life Cycle Cost (LCC) analysis in order make this system a reality.

I. INTRODUCTION

A. MOTIVATION

> *The successful missile test was part of a regular military exercise conducted by our military to boost our self-defense," a North Korean foreign ministry spokesman was quoted as saying. "As a sovereign country, this is our legal right and we are not bound by any international law or bilateral or multilateral agreements ... if anyone tries to discuss the rights and wrongs about [future tests] and apply pressure, we will be forced to take physical actions of a different nature. Justin McCurry, in Tokyo and agencies in Washington, July 7, 2006, The Guardian*

> *The threat we face from proliferating and evolving ballistic missile systems and associated technologies and expertise continues unabated. There were nearly 100 foreign ballistic missile launches around the world in 2004. This is nearly double the number conducted in 2003 and slightly greater than the number of launches in 2002. More than 60 launches last year involved short-range ballistic missiles, over ten involved medium range missiles, and nearly twenty involved land- and sea-based long-range ballistic missiles. Lieutenant General Henry A. Obering III, USAF Director, Missile Defense Agency Missile Defense Program and Fiscal Year 2006 Budget Spring 2005*

The threat from ballistic missiles to the U.S. and its allies is ever increasing in quantity and capability. The recent war in Lebanon has seen hundreds of small rockets launched into Israel. Had Hezbollah gained access to longer range missiles, much greater damage to property and loss of life throughout Israel could have occurred. North Korea flexed its military muscle on 6 July, 2006 with the test firing of seven ballistic missiles in one day, including a Taepo Dong II. While the failure of the dual stage Taepo Dong II, capable of reaching over 5000 kilometers into U.S. soil, captured all the attention, the success of the other 6 missiles shows an increasing capability of this rogue nation. BMD will be a common theme of military for years if not decades to come. “The Missile Defense Agency (MDA) mission remains one of developing and incrementally fielding a joint, integrated, and multilayered BMD system to defend the United States, our deployed forces, and our allies and friends against ballistic missiles of all ranges by engaging them in the boost, midcourse, and terminal phases of flight.”[4]

This paper explores a VHF / UHF ship-based OA radar, called the DARBC, and describes the operational and technical requirements for this notional system. The combination of a large effective radar aperture created by the OA and relatively low VHF / UHF transmit frequencies are expected to allow the DARBC system to achieve the long detection ranges needed by the MDA. These attributes may also provide the added advantage of being able to detect and track targets with low RCSs such as stealth aircraft and missiles.

B. PREVIOUS WORK

This document is a continuation of design and development of a three-dimensional UHF/VHF digital phased array radar against ballistic missiles using new aperstructure opportunistic array radar concept generated by Naval Postgraduate School (NPS) students Lance Esswein[5], Cher Eng[6], Chin Ong[7], and Matthew Tong[8]. Esswein studied and demonstrated use of the AD8346 and AD8347 T/R modulator and demodulator chips as phase shifters and variable attenuators. Eng researched the capability of using Commercial-Off-The-Shelf (COTS) modulation boards from the 3-D 2.4 GHz phase array antenna. Ong researched different options in the use of Direct Digital Synthesizer (DDS) in pulse radar and continuous wave radar. Tong's studied the opportunistic array concept for ballistic missile defense and on designing a low-profile, broad-band U-slot microstrip patch antenna. This work provided guidelines for the current DARBC study and the concept was used to demonstrate that DARBC radar can first detect ballistic missiles at 2000 km and designate to S-band fire control radar for engagement.

C. SCOPE OF PROJECT AND PAPER ORGANIZATION

1. Scope and Tasking from NPS

This project was based on tasking from the Naval Postgraduate School (NPS) in a proposal made to the MDA[9] to provide a detailed radar systems analysis and parameter tradeoff study for a long-range VHF / UHF OA Surveillance Radar (OASR). The tasking further requested operational and technical requirements along with the resultant impact to ship. Discussions with faculty advisors provided initial assumptions which included

limiting research on ship integration impacts. The project assumes that an aperstructure concept, or combination of radar aperture with ship's structure would be utilized and the DARBC radar would be implemented in a new ship design[10, 11]. Detailed integration and back-fit considerations were eliminated from the scope.

2. Organization

Chapter II provides the CONOPS which describes the ballistic missile defense mission and the benefits that a long range mobile sensor could provide. The CONOPS also provides a detailed threat description including RCS analysis which is required for some of the modeling efforts provided in Chapter IV. Chapter II presents the Operational View (OV-1) for the radar and basic scenarios for its use which will apply for modeling efforts described in Chapter IV.

Chapter III provides the operational and technical parameters of the DARBC system as requested under the NPS tasking[9]. These requirements are further detailed in the ICD[1] and CDD[2]. Radar parameters of interest including array density, capability to support EA, recommendations for search patterns, and cooling requirements of T/R modules are also provided. Ship flexure contributions to system error budgets for the large scale radar are discussed along with potential dynamic compensation methods. Program considerations for supportability and risk areas for program costs are also included in this chapter.

Chapter IV provides a description of modeling efforts and presents the basic results from analysis performed on RCSs of threat, radar performance parameters, and system reaction time improvements with DARBC.

Chapter V provides the results of analysis and overall project conclusions and recommendations.

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II. CONCEPT OF OPERATIONS AND THREAT DESCRIPTION

A. CONCEPT OF OPERATIONS

The DARBC radar will provide long-range search, detection and track of the various types of ballistic missiles for cueing to other organic sensors or systems in an overall Joint Battle Management Command and Control (JBMC2) network. The radar will provide early detection of ballistic missile launches over large areas of land or sea space not currently or adequately covered by existing sensors. Ships configured with DARBC will be forward deployed to positions where they have the greatest potential for detection of launches. Early detection and tracking increases overall engagement timeline, providing more time for decision making, weapon assignment, and weapon engagement from the overall BMD family of systems. Early detection using forward based sensors permits engagement of ballistic missile threats during boost and ascent phase when the threats are slower, larger and easier to engage. The early detection, track and cueing will also improve engagement by other BMD systems that engage the threat in midcourse or terminal phases of flight. Deployment of the ship to provide midcourse and terminal search, detection, and tracking of ballistic missiles is possible as well. Secondary benefits include search, detection and track of all stealth air threats. Detection of these threats will be at ranges where they pose a secondary threat to the ship or units in the immediate operational area either by launch of weapons or as weapons themselves. The radar also could provide tertiary benefits to support VHF / UHF communications either in Line Of Sight (LOS) or by SATCOM link.

1. BMD Mission

BMD is best accomplished using a layered defense/combined arms approach. [12] There are too many threats in existence to rely on hard kill defenses only.[12] Many countries can launch multiple salvo threats and from many locations. The best overall strategy will entail systems to attrite enemy capability using Information Operations (IO) / Electronic Attack (EA) / Strike in addition to hard kill of threats in flight. Current Navy BMD capability is based on the STANDARD Missile 3 (SM-3) launched from Aegis ships. Depth of fire with SM-3 is limited during an engagement from one

platform– generally one, max of two. Maximum effectiveness of Aegis and SM-3 can be achieved when reaction time is improved by cueing and positioning the Aegis platform for an engagement and allowing other sensors to be positioned for early detection and cueing. Detection of ballistic missiles can be enhanced from prior knowledge of launch location, time and target type. When intelligence can provide some of this information, especially location, specific search patterns can be generated to increase probability of detection. Space based assets can monitor large areas and cue sensors when launches have been detected. As a forward deployed combatant, the ship will potentially be exposed to direct attack by the state posing the ballistic missile threat. The ship and radar will be able to counter threats of anti-ship cruise missiles through hard kill methods. The radar design and ship integration shall not increase the RCS signature. The ship/radar will be available on station for long periods of time, regardless of weather and sea conditions. When the ship is positioned to defend a terminal position, the radar must be capable of detecting the threat at ranges suitable for terminal engagements. These threats can include single or multiple re-entry vehicles (RV) which may be obscured by associated debris and decoys.

2. Threat Summary

The Radar will be deployed to support one of two basic missions. The first is to be forward deployed near a projected threat country or area positioned to search for ballistic missile launches. The second is a homeland defense position where the ship will be positioned to detect sea based launches from submarines or undisclosed threat surface ships. The forward deployed scenario could put the ship in a position where it is in harms way. Because the time line between detection and engagement is very short, shooters armed with very fast interceptors or lasers must be stationed close to the launch location. The proximity of this position to the threat means the ship is subject to attack. The ship will be subject to the same threats posed to current and future surface combatants such as Anti Ship Cruise Missiles (ASCMs) and other air, surface, and subsurface threats. The ship can be expected to be deployed and positioned for long periods of time while on station providing surveillance.

The ship/radar would normally be operated in conjunction with other BMD units. These units could be Patriot or Aegis platforms providing terminal phase defense. When long-range ballistic missiles are launched, BMD fixed assets in Alaska or Continental United States (CONUS) will be cued to support midcourse tracking in support of ground-based interceptors or other engagement means.

Ballistic missiles have proliferated over the last four decades and are now prevalent across the globe with over 24 countries capable of launching some form of this threat. As an example, over 100 foreign ballistic missile test launches occurred around the world in 2004. Many countries also have the capability to configure these missiles with Weapons of Mass Destruction (WMDs) including nuclear, chemical and biological payloads. Additionally, submarines can launch ballistic missiles, dramatically increasing threat launch areas, escalating the need for sea-based sensors with enhanced capabilities in search volume[4]. Ballistic Missiles are classified in the following 5 main categories as described by Table 1.

Ballistic Missile Category	Maximum Range	Apogee
Short-range ballistic missile (SRBM)	<1,000 km(621 mi)	160 km
Medium-range ballistic missile (MRBM)	1,000-3,000 km (621-1,864 mi)	500 km
Intermediate-range ballistic missile (IRBM)	3,000-5,500 km (1,864 – 3,418 mi)	900 km
Intercontinental ballistic missile (ICBM)	>5,500 km (3,418 mi)	2500 km
Submarine-launched ballistic missile (SLBM)	Any ballistic missile launched from a submarine, regardless of maximum range	Varies

Table 1. Ballistic Missile Flight Path Characteristics[13]

The range and apogees reported are estimated maximum capabilities. These weapons can support shorter ranges with lower or depressed apogees. Some may fly a trajectory that has a lower apogee to achieve maximum range. A ballistic missile is a

projectile that has been given some level of initial power, operates at or below the exo-atmosphere, and after boost, follows a path governed mainly by the laws of gravity. Notional trajectories for the above categories are depicted in the Figure 1.

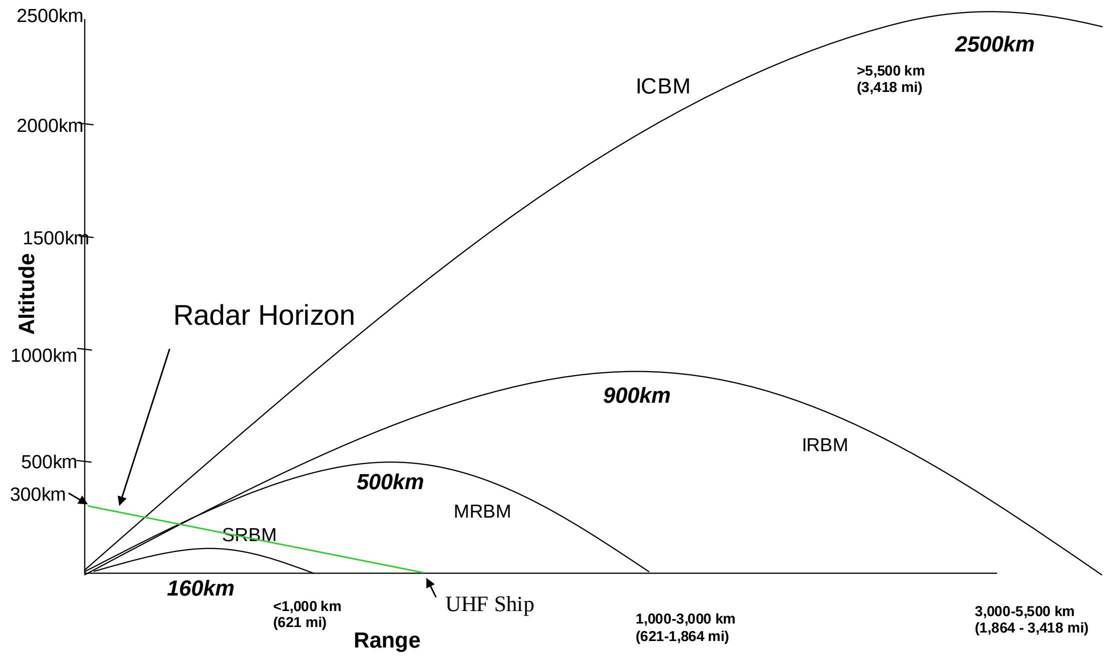

Figure 1. Ballistic Missile Flight Paths

Tactics for deploying these threats will involve surprise. Submarine launched threats are based on a stealthy launch platform that can hide its position and intent until after weapons release. Many BMD threats are launched from Transportable Erectable Launchers (TELs) that can hide their positions, then erect and launch in just a few minutes. TELs can virtually be hidden within the boundaries of an entire country. ICBMs are typically housed in silos that have known positions. While the known location of these launchers may help in destruction when rules of engagement permit, initial launches in an unprovoked attack may provide with little to no warning.

3. Operational View and Scenarios

The DARBC OV-1, Figure 2, depicts the ship providing forward deployed support sensor coverage for ballistic missile defense.

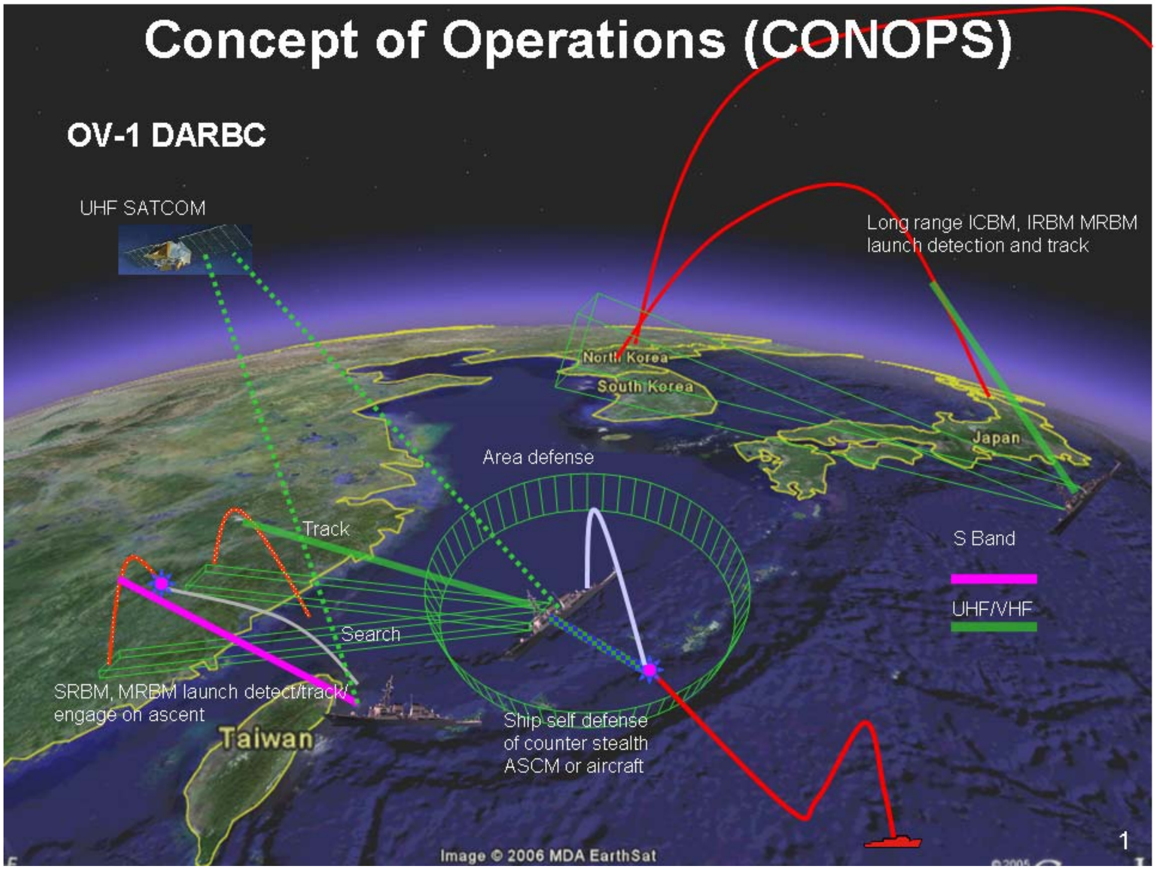

Figure 2. DARBC Operational View

The following scenarios are possible:

- DARBC ship forward deployed close to launch point and cueing S-Band or other sensors for mid-course or terminal engagement.
- DARBC ship forward deployed close to launch point for engagement by own weapons. Cue to Weapon Control Sensor (WCS).
- DARBC ship deployed in linebacker position with forward deployed S-Band sensors and engagement receiving cue from DARBC.
- DARBC ship deployed in homeland defense mission to detect submarine or surface ship launched ballistic missiles.

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III. SYSTEMS ENGINEERING ANALYSIS OF REQUIREMENTS DEVELOPMENT FOR OPPORTUNISTIC ARRAY RADAR

A. DARBC PERFORMANCE PARAMETERS

This section identifies the operational and technical requirements for the DARBC and defines thresholds and objectives for these parameters. Further details on the radar requirements can be found in the ICD[1] and CDD[2] for the DARBC system. A summary of the KPPs for the DARBC is shown in Table 2.

(U) Key Performance Parameters			
Key System Characteristics	**Attribute**	**Development Threshold**	**Development Objective**
Detection			
	Detection Range	748 km	1000 km
	Probability of Detection	0.90	0.95
Acquisition			
	Probability of Track	0.90	0.95
Track Accuracy			
	Azimuth	± 0.5°	± 0.2°
	Elevation	± 0.5°	± 0.2°
	Range	± 0.5 km	± 0.2 km
	Velocity	± 100 m/sec	± 80 m/sec
Reliability			
	Mean Time Between Operational Mission Failures (Hardware) ($MTBOMF_{hw}$)	(U) 130.0 Hrs	(U) 130.0 Hrs
	Mean Time Between Operational Mission Faults (Software) (MTBOMFsw)	(U) 25.0 Hrs	(U) 25.0 Hrs
Maintainability			
	Mean Corrective Maintenance Time for Operational Mission Failure (Hardware) ($MCMTOMF_{hw}$)	(U) 2.0 Hrs	(U) 2.0 Hrs

(U) Key Performance Parameters			
Key System Characteristics	**Attribute**	**Development Threshold**	**Development Objective**
	Mean Corrective Maintenance Time for Operational Mission Failure (Software) ($MCMTOMF_{sw}$)	(U) 18 sec	(U) 18 sec
	Scheduled Maintenance Time Per 24 Hours	(U) 2.0 Hrs	(U) 2.0 Hrs
	Restoration Time (Max Time) (From Scheduled Maintenance)	(U) 10.0 Min	(U) 10.0 Min
	Restoration Time (Max Time) (From System Test)	(U) 3.0 Min	(U) 3.0Min
Availability			
	A_o (Ballistic Missile Defense Mission Profile)	(U) 0.9	(U) 0.9

Table 2. KPPs for the DARBC System

1. Operational Parameters

The Radar antenna performance shall satisfy the following DARBC operational requirements: Detection Range, Probability of Detection, Probability of Acquisition, Track Accuracy, Reliability, Maintainability, and Availability (RM&A).

a) Detection Range

The DARBC system shall have the capability to detect the signal returned from a notional ballistic missile target characterized by a 10 m^2 RCS[14] at the handoff range of 748 km[15] where the DARBC would likely cue the S-band radar in order to engage the threat with a signal to noise ratio sufficient to exceed the receiver's sensitivity threshold. The notional ballistic missile target described in this project is defined as having a 77m^2 RCS in the UHF band and a 146 m^2 RCS in the VHF band[14]. It shall provide consistent, timely, and accurate target information in any environmental conditions.

b) Probability of Detection

The DARBC system shall have 0.90 P_D on a notional ballistic missile target described in the section 6.1 at a range of 748 km.

c) Probability of Track

The DARBC system shall have 0.90 probability of track on a notional ballistic missile target described in the section 6.1 at a range of 748 km.

d) Track Accuracy

At the conclusion of the acquisition cycle, the DARBC shall be capable of providing position and velocity information on the target. Azimuth and elevation shall be accurate within $\pm 0.5°$. Range shall be accurate within ± 0.5 km. Velocity shall be accurate within $\pm$ 100 m/s.

e) Reliability, Maintainability, and Availability

The DARBC system shall be capable of meeting the reliability, maintainability, and availability thresholds of Mean Time Between Operational Mission Failures (Hardware) ($MTBOMF_{hw}$) of 130 Hrs, Mean Time Between Operational Mission Faults (Software) (MTBOMFsw) of 25 Hrs, Mean Corrective Maintenance Time for Operational Mission Failure (Hardware) ($MCMTOMF_{hw}$) of 2 Hrs, Mean Corrective Maintenance Time for Operational Mission Failure (Software) ($MCMTOMF_{sw}$) of 18 sec, Scheduled Maintenance Time Per 24 Hours of 2 hrs, Restoration Time (Max Time) (From Scheduled Maintenance) of 10 min, Restoration Time (Max Time) (From System Test) of 3 min, and A_o (Ballistic Missile Defense Mission Profile) of 0.90.

2. Technical Parameters

a) Value Calculations

Radar systems like the DARBC can be technically described by the radar equation. The radar equation is made up of parameters which represent characteristics of the radar, the target, and the operational environment. The parameters can be optimized for maximum operational performance using the equation. The optimized values for

these parameters will be the technical requirements for the system so that it will be capable of achieving the KPPs specified in the CDD[2].

Equation 3.1 is the radar equation solved for Signal to Noise Ratio (S/N). Note that in this equation, S/N is a dimensionless value, not in dB.

$$\frac{S}{N} = \frac{P_t G A_e \sigma n E_i(n)}{(4\pi)^2 k_b T_o B_n F_n R_{\max}{}^4} \tag{3.1}$$

Equation 3.2 is the relationship between S/N and the P_D and False Alarm (P_{FA}). In this relationship, S/N is in dB.

$$\frac{S}{N} = \frac{(\log_{10} P_{FA} - \log_{10} P_D)}{\log_{10} P_D} \tag{3.2}$$

Equations 3.1 & 3.2 can be combined to form Equation 3. 3. This equation is the base of the radar parameters analysis, allowing for the radar parameters to be adjusted so that the detection probability can be graphed as a function of range.

$$\frac{(\log_{10} P_{FA} - \log_{10} P_D)}{\log_{10} P_D} = \frac{S}{N} = 10 \times \log_{10}\left(\frac{P_t G A_e \sigma n E_i(n)}{(4\pi)^2 k_b T_o B_n F_n R_{\max}{}^4}\right) \qquad 3.\ 3$$

The overall approach for the analysis was to first look at the way in which the DARBC would be used in operation. Current S-band radars used by the U.S. Navy to search for ballistic missiles use up a lot of resources in search mode and are actually capable of tracking targets at ranges greater than their maximum search range. The DARBC will provide a benefit to current S-band radar systems by extending the search capability to detect ballistic missiles and cueing the S-band systems to track the target at a range that would have been outside the search range for the S-band radar alone.

Analysis using Equation 3. 3 was first conducted for a notional S-band radar to form a baseline needed to determine at what maximum range the current radar will be able to accurately track a ballistic missile if cued by the DARBC. A P_D vs. Range plot was generated for the S-Band radar with parametric curves on the graph for different RCSs. Since the predicted RCS for a notional ballistic missile is $10m^2$ in the S-band frequency (assuming an aspect angle of 88.46°) equaling to $77m^2$ in the UHF band and $146m^2$ in the VHF band at the same aspect angle[16], the generated plot can be analyzed to see at what range the S-band radar would have a P_D of 0.5 for this RCS. This range will be the desired track handoff range from the DARBC to the S-Band radar.

Following the analysis on the S-Band radar, the same analysis was generated to analyze the capabilities of the DARBC. The approach said that the DARBC should be capable of tracking the notional ballistic missile with a P_D of 0.90 at the handoff range to the S-Band radar. The Range / P_D combination will drive one of the KPPs for the DARBC system. The radar parameters for the DARBC were tuned so that this goal can be met and that the parameters used are feasible.

The values for the parameters listed in Equation 3. 3 for the DARBC were derived using this equation and other equations to be described in this section. Analysis and calculations described in this section were conducted using Waterloo Maple® 7 Computer Algebra System (CAS). Initially, notional values were used as the radar equations were set up in the Maple code. After the completion of the Maple code, the values of the various parameters were researched, manipulated and analyzed for their affect on the overall P_D as well as their feasibility.

Equation 3.4 calculates the wavelength (λ) for a given frequency. Calculations were done using one VHF (216 MHz) and one UHF (420 MHz) frequency for the DARBC. For the notional S-band radar, a frequency of 3 GHz was used. In this equation, *c* is the speed of light.

$$\lambda = \frac{c}{f} \tag{3.4}$$

Equation 3.5 is the equation used to calculate the Antenna Effective Aperture (A_e). A typical value of 0.7 was used for Effective Aperture Efficiency η.[17] Analysis on the array element density shows that there are can be up to 2 elements / m^2 on the DARBC aperstructure.[18] With this specified density, A_e can be calculated based on the number of elements within the aperstructure which contribute to a single beam (n) multiplied by the efficiency η. Based on a notional hull for a new construction ship, it was found that 3411 elements can be placed one side of the ship. For this research, 3411 was used for n but sensitivity analysis was conducted which relates P_D to n.

$$A_e = n \times \eta \tag{3.5}$$

Equation 3.6 shows that Gain (G) is calculated based on the A_e and λ.

$$G = \frac{A_e 4\pi}{\lambda^2} \tag{3.6}$$

Doppler Shift (f_D) occurs when the target being tracked is non-stationary. The echo returning to the radar receiver will be higher or lower in frequency than the transmission wave depending on if the target is closing or moving away from the radar (See Figure 3). Using the maximum predicted velocity for a ballistic missile, f_D was calculated. Based on this f_D value, receiver noise bandwidth (B_N) was calculated to be double the value of f_D so that the DARBC would be able to track targets coming towards or going away from the radar. Calculations for B_N for the UHF and VHF frequencies are shown below. These values were used as inputs to the Maple program.

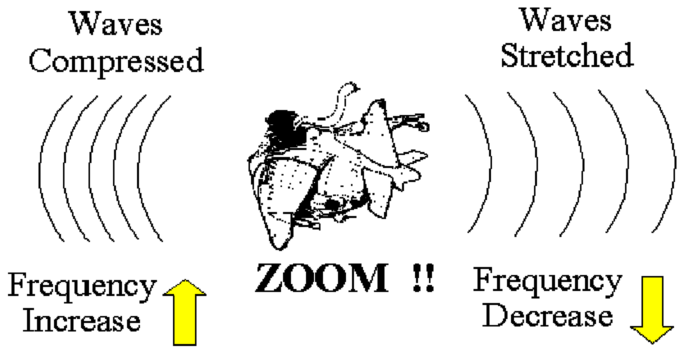

Figure 3. Illustration of the Doppler Shift Effect

Doppler Shift and B_n[19]

Rules of Thumb for two-way signal travel

(divide in half for one-way ESM signal measurements)

At 10 GHz, f_D = 35 Hz per Knot

= 19 Hz per km/Hr

= 67 Hz per m/sec

= 61 Hz per yd/sec

= 20 Hz per ft/sec

To estimate f_D at other frequencies, multiply these by:

$$\left[\frac{f_{Xmt}\ (\text{GHz})}{10}\right]$$

Ballistic Missile travels at 7.5 km/s (max) = 27000 km/hr

$$f_{D\,(VHF)} = \frac{19\ \text{Hz}}{\text{km/hr}} \times \frac{27000\ \text{km/hr}}{1} \times \frac{0.216\ \text{GHz}}{10} = 11.08\ \text{kHz}$$

$$B_{n(VHF)} \geq 2\times\ f_{D(UHF)} = 23kHz$$

$$f_{D\,(UHF)} = \frac{19\ \text{Hz}}{\text{km/hr}} \times \frac{27000\ \text{km/hr}}{1} \times \frac{0.420\ \text{GHz}}{10} = 21.55\ \text{kHz}$$

$$B_{n(UHF)} \geq 2\times\ f_{D(VHF)} = 44kHz$$

Based on the Maple calculations and parameter sensitivity analysis, the following parameters were used for the DARBC and S-band radar calculations (Table 3). The values listed for the DARBC in this table are the recommended values for the DARBC technical parameters.

Parameter	**Description**	**Value Used**	**Maple Name**
P_{max}[20]	Transmitted power [W]	500 kW (VHF, UHF), 4 MW (S-band)	P (VHF & UHF), P2 (S-band)
σ[21]	Radar cross section of target [m^2]	146 (VHF), 100, 77 (UHF), 10, 1, 0.1 [m^2]	H1V (146), H1 (100), H1U (77), H2 (10), H3 (1), H4 (0.1)
n	Number of pulses integrated	1	N
$E_i(n)$	Integration efficiency	1	E
k_B	Boltzmann's constant [J/degree K]	1.3806503E-23 J/ K	K
T_0	Standard temperature [degrees K]	290 degrees K	T
B_n	Receiver noise bandwidth [Hz]	23 kHz (VHF), 44 kHz (UHF), 4 MHz (S-band)	B1 (VHF), B2 (UHF), B3 (S-band)
F_n[22]	Receiver noise figure	$1\times10^{3/5}$ = 6 dB	F
P_{FA}	Probability of False Alarm	0.01	fa
f[23]	Radar Transmit Frequency	216 MHz (VHF), 420 MHz (UHF), 3 GHz (S-band)	f1 (VHF), f2 (UHF), f3 (S-band)
η[24]	Effective Aperture Efficiency	0.7	Ef
n[25]	Number of Array Elements contributing to 1 beam	3411	n
λ	Wavelength [m]	1.3879 (VHF), 0.7138 (UHF), 0.0999 (S-band)	WL1 (VHF), WL2 (UHF), WL3 (S-band)
A_e	Antenna effective aperture [m^2]	This is a function of n and η; 1193.85 (VHF & UHF), 17.5 (S-band)	A1 (UHF), A2 (VHF), A3 (S-Band)

Parameter	Description	Value Used	Maple Name
G	Antenna gain	This is a function of A_e and λ; 38.9 dB (VHF), 44.7 dB (UHF), 43.4 dB (S-band)	G1 (VHF), G2 (UHF), G3 (S-band)
S/N	Signal-to-noise ratio (SNR) required for detection based on a single pulse	Not directly calculated. This is a function of R_{max}.	S1 (VHF), S2 (UHF), S3 (S-band)
R_{max}	Maximum radar range or detection range [m]	Variable (see plot)	R
P_D	Probability of Detection	Variable (see plot)	D

Table 3. Parameter Values Used in the Maple Analysis

Based on these values above, the "Handoff Range" where the DARBC will cue the S-band radar to track a ballistic missile target will be 748 km. This is the range where the S-band radar has a P_D of 0.5 for an RCS of 10 m^2 (See Figure 4). Ignore the vertical lines on these plots as they are an artifact of Maple where the values go to zero.

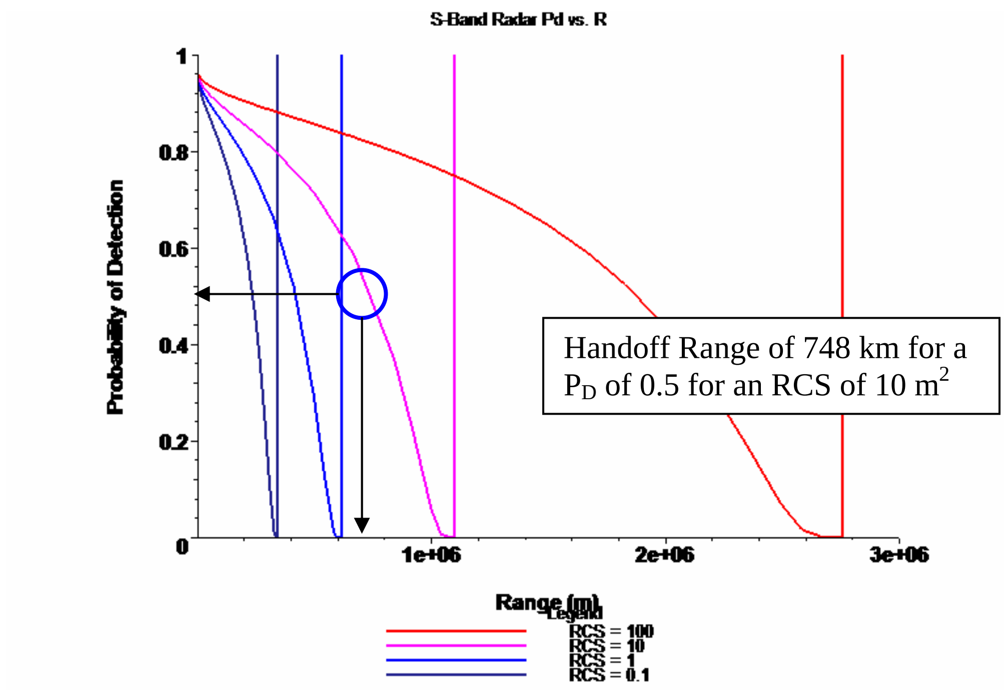

Figure 4. Calculated Handoff Range to S-Band Radar

The DARBC should have a 0.90 P_D at this range of 748 km vs. a similar ballistic missile target (RCS of 146m^2 for VHF and 77m^2 for UHF). Using parameters from Table 3, the Maple model shows that the DARBC is able to obtain 0.906 ≈ 0.91 P_D using both VHF and UHF spectrums. Shown in Figure 5 and Figure 6 below is the anticipated performance level, P_D vs. Range for VHF and UHF, of the DARBC system, using the parameters from Table 3.

```
> VHFPsubD:=evalf(eval(P4VHF,R1=748000),5);#VHF Pd at handoff range vs. Ballistic
Missile (146m^2 RCS)
```

$$VHFPsubD := .90616$$

```
> UHFPsubD:=evalf(eval(P4UHF,R2=748000),5);#UHF Pd at handoff range vs. Ballistic
Missile (77m^2 RCS)
```

$$UHFPsubD := .90651$$

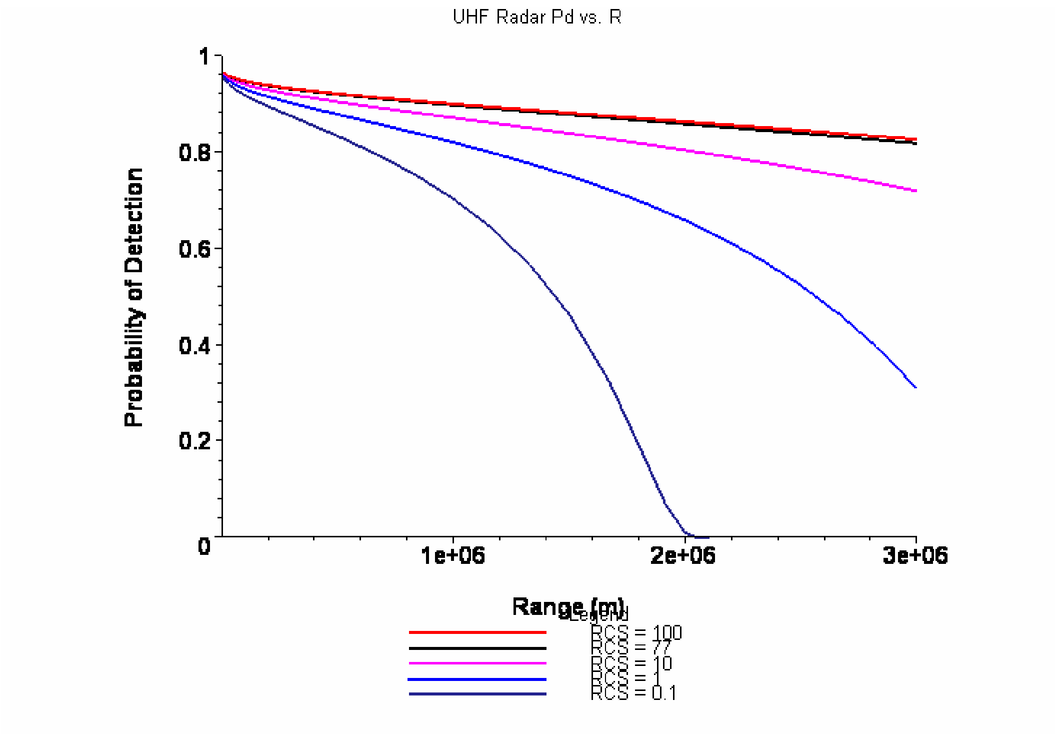

Figure 5. DARBC P_D vs. Range Performance Using the UHF Spectrum

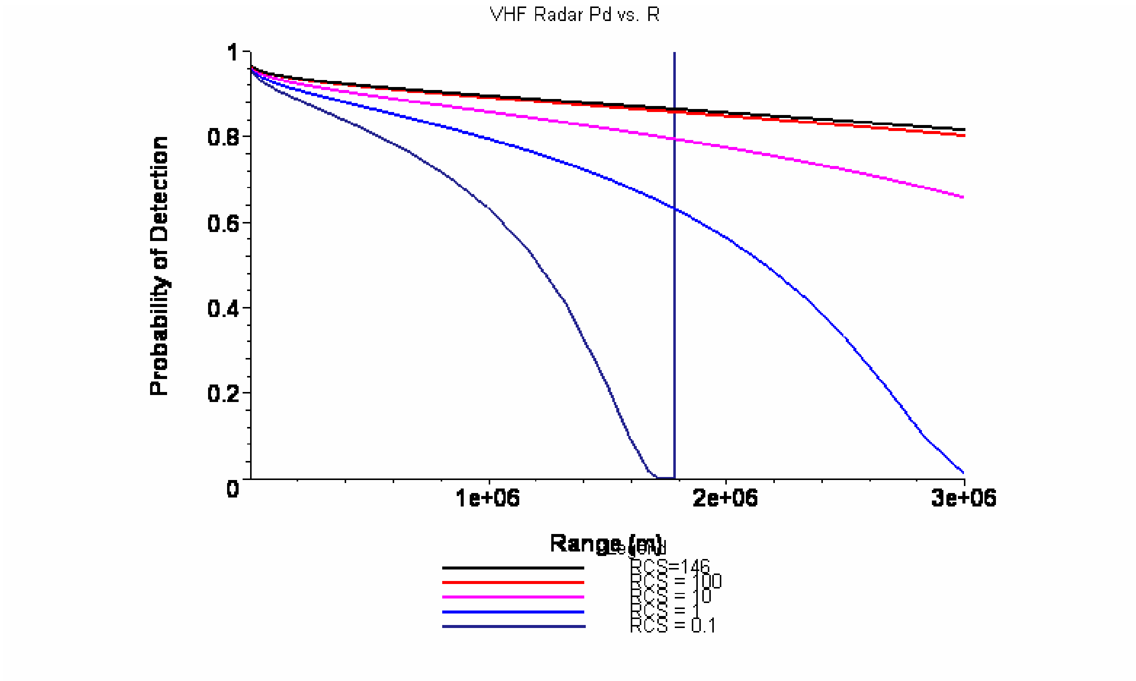

Figure 6. DARBC P_D vs. Range Performance Using the VHF Spectrum

The current model (using parameters defined in Table 3) of the DARBC shows that the radar system will be capable of meeting its KPP of a 90% P_D at the handoff range (748 km) against a notional ballistic missile target however, sensitivity analysis was performed on various parameters to see how easily P_D could be raised for the DARBC. Power, Gain, and number of elements were analyzed against P_D at the handoff range to see if minor adjustments could increase the predicted performance.

b) Sensitivity Analysis

(1) Power Sensitivity

Power sensitivity analysis shows that major increases in P_T would not bring the performance of the DARBC up significantly. As shown in Figure 7 and Figure 8, increased levels in power beyond several tens of kW have a mild affect on P_D. Power levels for the DARBC would have to be raised to an unfeasible level in order to have an increase of 1 – 2 % in P_D. The power parameter is a conservative estimate of 500 kW. For that number of elements, the system may be capable of radiating at a much

higher power level. Increasing the power would only increase the P_D values for the radar and the power was left at its current level in the Maple ® model.

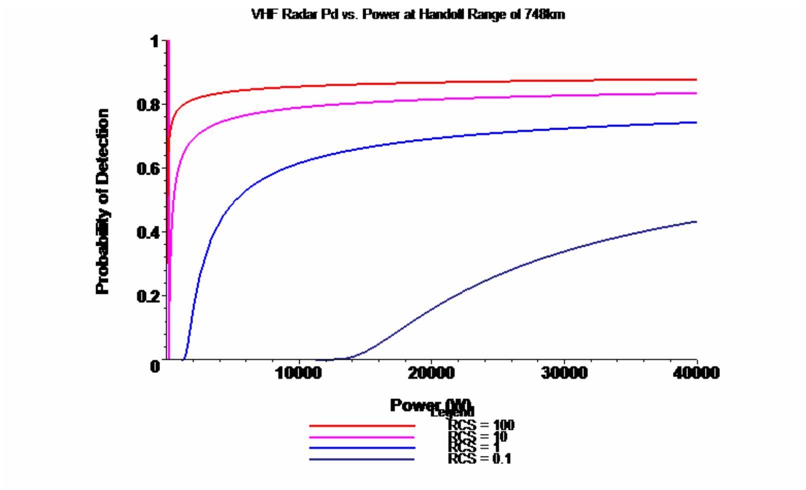

Figure 7. VHF Radar P_D vs. Power at a Range of 748 km

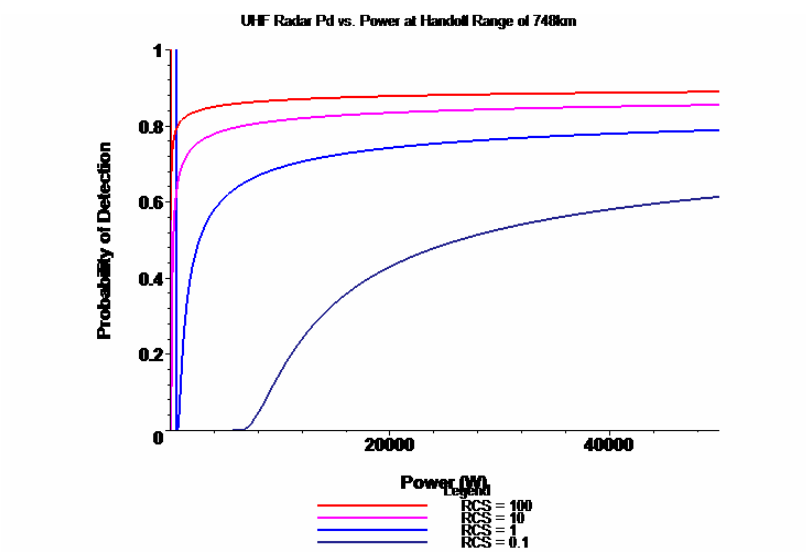

Figure 8. UHF Radar P_D vs. Power at a Range of 748 km

(2) Gain Sensitivity

Gain sensitivity analysis shows that increases in G of about 10dB or so have the ability to increase the performance of the DARBC with some level of significance depending on the RCS of the target. The smaller RCSs will benefit more from this type of adjustment to the radar parameters. See Figure 9 and Figure 10 for the gain sensitivity analysis.

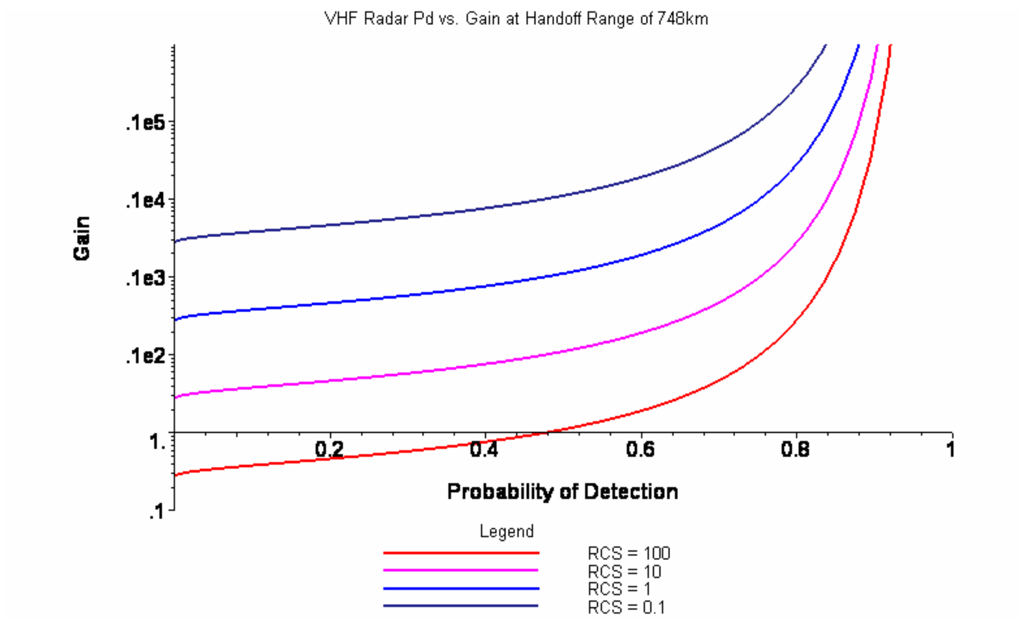

Figure 9. VHF Gain vs. P_D at a Range of 748 km

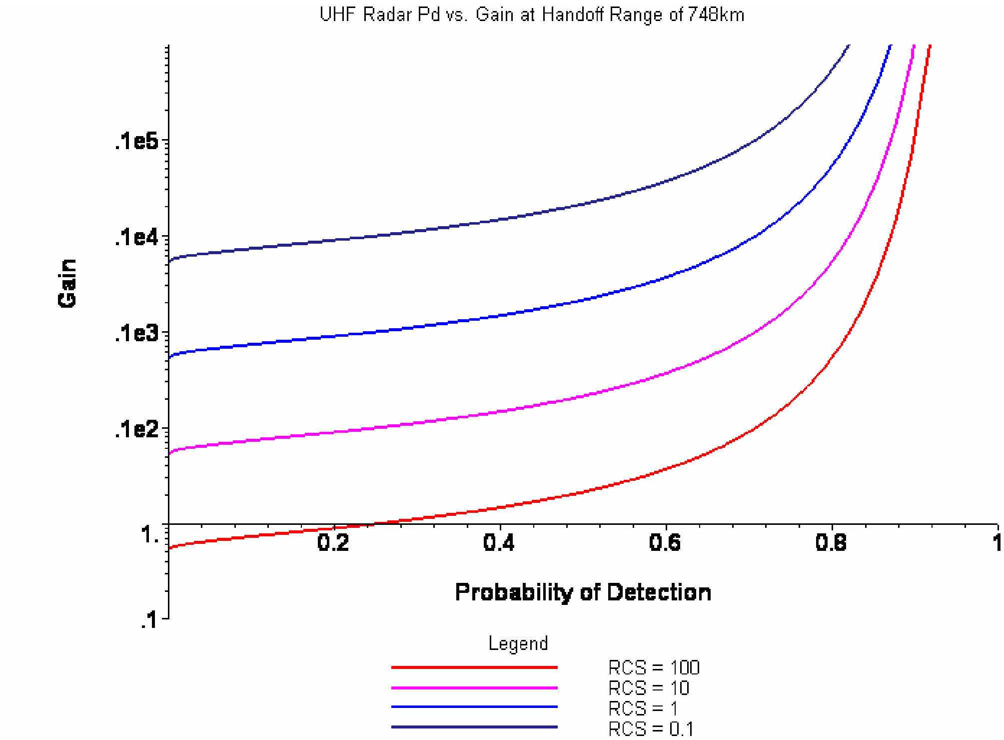

Figure 10. UHF Gain vs. P_D at a Range of 748 km

(3) Aperstructure Size Sensitivity (number of elements)

Since G is a function of λ and A_e, further analysis was needed to look into A_e since λ is fixed at the VHF and UHF bands. A_e is dependent on the number of elements in the array as they are fixed in size. Figure 11 shows the sensitivity curves for number of elements as a function of P_D for the DARBC using the VHF spectrum. There is some level of performance to gain by boosting the number of active elements for the lower RCSs for this system.

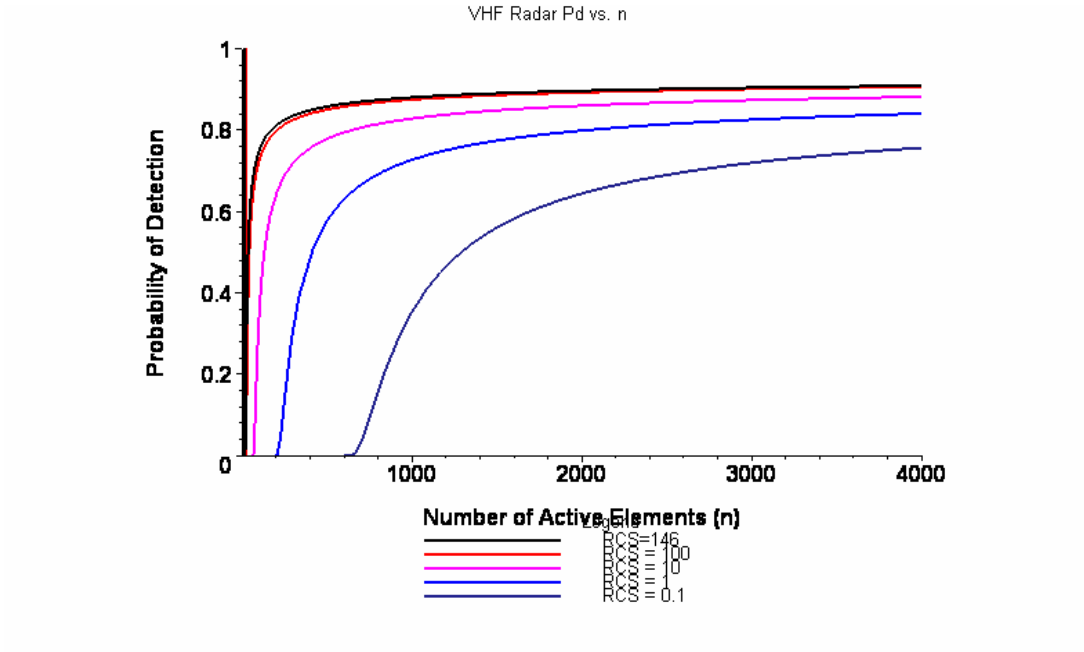

Figure 11. VHF P_D vs. Number of Elements at a Range of 748 km

Results show that an increase in the number of active elements, from the value specified in Table 3, will have a minor but still significant affect on P_D against targets with lower RCS values. However, this sensitivity analysis also shows the impact of having fewer elements than the number specified in Table 3.

3. Array Element Density and Integration

"Phased array radars are most commonly designed as periodic arrays. In developing the aperstructure concept, however, it is important investigate if aperiodic arrays are able to achieve comparable performance. This is because the ship's superstructure makes it physically unfeasible to implement a uniform, periodic array over the entire ship's structure. In addition, integrating an array of closely spaced antenna elements across the entire ship's structure is impractical and likely to be extremely costly.

Density requirements for T/R elements of the DARBC system is needed in order to define radar parameters including total power, peak power, shape of the radar beam and antenna efficiency. The array density requirements will help determine how the radar system would be implemented and operated.

Periodic array designs typically maximize the spacing between individual antenna elements yet keep it small enough to eliminate grating lobes. Equation 3.7 shows the condition for avoiding grating lobes under all conditions of beam-steering.

$$d \leq \frac{\lambda}{2} \tag{3.7}$$

One of the inherent disadvantages to using this spacing between OA elements is the effect known as mutual coupling.

Mutual coupling occurs between closely spaced antenna elements. Coupling may occur by radiation, from surface paths, from paths within the feed structure, or from reflections at the antenna terminal due to impedance mismatches. The effects of mutual coupling include distortions in the radiation pattern and variations in the element gains. Mutual coupling may be characterized by a coupling coefficient c_{mn} that relates the current flowing into the n^{th} element due to the current from the m^{th} element. Equation 3.8 shows this coefficient for isotropic elements.

$$c_{mn} = \frac{\sin(kd_{mn})}{kd_{mn}} \tag{3.8}$$

d_{mn} = distance between n^{th} and m^{th} elements

The figure below graphs the relationship between the mutual coupling coefficient and the separation between antenna elements. Observe that the equation for c_{mn} is simply a sinc function. Hence, the effects of mutual coupling are undulatory with the distance between the elements with the envelope of the coupling coefficient decreasing with separation.

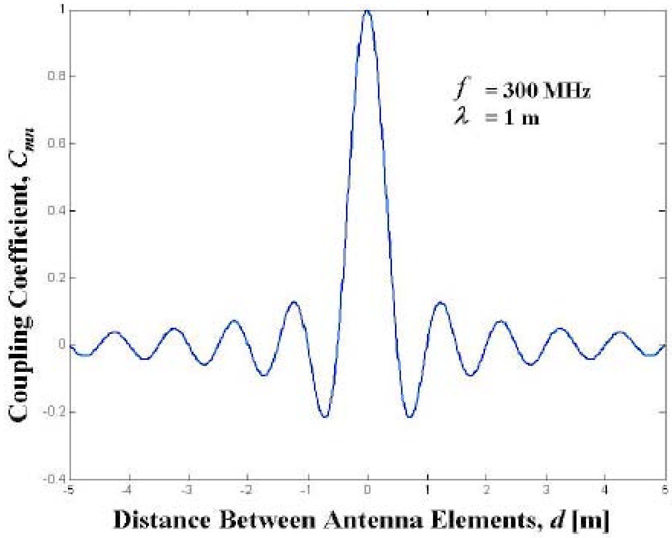

Figure 12. Coupling Coefficient vs. Separation of Antenna Elements[8]

Theoretically, the effects of mutual coupling can be calculated and hence compensated. In reality, the coupling coefficient is not easily measured, is not stable with scan angle and is not conveniently controlled – especially for large ship-sized arrays which are too big to be tested in a controlled environment. The best way to reduce the effects of mutual coupling is to increase the distance between individual antenna elements beyond the requisite $\frac{\lambda}{2}$ criteria presented in the Equation 3.8. This process is commonly known as "thinning". This approach, however, can result in higher sidelobes and increased grating lobe levels unless an aperiodic array is designed.[8]

In order to have minimal interference between OASR elements the minimum physical spacing between the elements on the hull of the ship should be greater than ½ of the wavelength of the beam in use. The DARBC system will operate in the VHF (216-225 MHz) and UHF (420-450 MHz) frequency bands. Equations 3.9, 3.10, 3.11, and 3.12 show the calculation of the wavelengths for the extreme ends of the radar's spectrum.

$$VHF\lambda_{\max} = \frac{299{,}792{,}458m}{s} \times \frac{1}{216\times10^{6}\,Hz} = 1.3879m \qquad 3.9$$

$$VHF\lambda_{\min} = \frac{299{,}792{,}458m}{s} \times \frac{1}{225\times10^{6}\,Hz} = 1.3324m \qquad 3.10$$

$$UHF\lambda_{\max} = \frac{299{,}792{,}458m}{s} \times \frac{1}{420\times10^{6}\,Hz} = 0.7138m \qquad 3.11$$

$$UHF\lambda_{\min} = \frac{299{,}792{,}458m}{s} \times \frac{1}{450\times10^{6}\,Hz} = 0.6662m \qquad 3.12$$

The desired minimum spacing between elements (the spacing which will cause minimal interference at any frequency of operation) will have to be greater than ½ VHF λ (max) which is 0.694m. Our goal is to have this minimum separation between array elements in all directions of the aperstructure. This spacing will minimize phase interference between elements which plays a part in optimizing the DARBC's ability to have the narrowest beam possible. A one degree beam-width will translate to a 35 km beam-width at a range of 2000 km, so it is necessary to consider everything within the design of the radar which can influence the beam-width. A narrower wavelength separation may cause the beam to have a large scatter point when it illuminates the target thereby causing the convergent point of the beam to be off.

4. Electronic Warfare

EA is defined as the division of Electronic Warfare (EW) involving the use of electromagnetic or directed energy to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability[26]. EA includes actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum, such as Electronic Counter Measures (ECM) (jamming and deception) and employment of weapons that use electromagnetic, optical or directed energy as their primary destructive mechanism as in Electromagnetic Pulse (EMP) (lasers, RF weapons,

particle beams).[26] This section will discuss jamming and deception ECMs and destructive mechanisms that could be incorporated in the design of the DARBC.

The two types of EA which are used against enemy communications are jamming and deception. Jamming is also thought of as “Concealment or Masking”, which broadcasts high levels of radiation within the frequencies used by the enemy for communication. The objective is to overpower the communication systems such as UHF SATCOM systems by inhibiting the reception of the enemy messages. Deception or “Forgery” mimics signals to the enemy radar in an effort to confuse the enemy’s systems. To do this, the DARBC would have to be able to monitor (receive) enemy radar transmissions and imitate those signals and broadcast them back to the enemy receivers[27].

The main threats against the DARBC platform would be ASCMs. ASCMs can have various modes of guidance such as differential Global Positioning System (GPS), active homing, semi-active homing, heat seeking, TV or infrared (IR). If any of theses guidance modes can be interrupted or deceived then there is a greater potential of the ASCM missing the target.

Since the DARBC is a VHF/UHF radar and does not have the capability to transmit and receive on other frequencies, it is not likely that the DARBC would be very good as a deception ECM platform. ASCMs such as the Exocet use X-band active homing which is outside the range of the DARBC’s spectrum[28]. Since the DARBC spectrum does not coincide with the typical ASCMs radar guidance frequencies, it would not be effective for deception.

Based on the radar technical parameters research, the DARBC will be capable of producing in excess of 500 kW peak output signal. If all this power can be directed at an incoming ASCM at a relatively close range (compared to the DARBC’s typical search ranges), the DARBC can generate a Non-Nuclear Electro-Magnetic Pulse (NNEMP)[29]. In order to achieve the frequency characteristics of the pulse needed for optimal coupling into the ASCM, the addition of wave-shaping circuits and/or microwave generators need to be added between the DARBC radiating element and the antenna.

When NNEMPs are coupled with existing electronic systems such as ASCMs, damaging current and voltage surges can be induced on those systems causing failure[30]. The signals' power and the pulse of the signal are what drive the effectiveness of an NNEMP signal. Higher frequency signals such as microwave signals are more effective than lower frequencies[31], such as VHF or UHF. Due to the low operational frequencies, even with the high power output, the DARBC could not effectively deliver NNEMPs, even on close range targets.

Even with the ability to direct high amounts of energy, the DARBC would probably not be capable of emitting NNEMPs effectively as part of a platform self defense effort or short range offensive effort. The DARBC would not be a good candidate for an ECM platform which could produce jamming or deception forms of EA due to the limited bandwidth of the radar. However, if enemy communications were known to be operating in the VHF or UHF spectrums, the DARBC could be effective as an ECM generating platform.

5. Element Wireless Communications

Research indicated that there are many viable options for the implementation of the wireless communication architecture for the DARBC system. The scope of this paper originally considered investigation of wireless architecture options. However, the investigation was cancelled due to the change in guidance relating to ship integration work. A future study is still necessary to assess wireless communications architecture for shipboard integration and should be conducted as part of a more detailed ship integration research project.

6. Cooling Requirements

This section describes different methods of cooling. Tradeoffs are considered in order to satisfy a range of requirements. Tong[8] provided the thresholds for different types of substrate options that the T/R module may utilize. The substrate consists of a dielectric material that affects the electrical performance of the antenna, circuits and transmission line for the OASR. Information on the best methods to cool the T/R modules was examined[32, 33].

No initial attempt was made to define measures, thresholds or objectives for cooling. Cooling requirements to increase survivability and operational availability were identified by Tong[8]. Table 4 compares the relevant properties of various different substrate options. Substrate properties listed in the table include constant dielectric, loss tangent, dimensional stability, chemical resistance, and temperature range. In addition, the relative cost is also considered as part of this tradeoff study.

Substrate	Constant Dielectric	Loss Tangent	Dimensional Stability	Chemical Resistance	Temperature Range (F degree)	Relative Cost
Ceramic Substrates						
Alumina	9.8	0.0004	Excellent	Excellent	to +1600	Medium to high
Sapphire	9.4, 1.6	0.0001	Excellent	Excellent	-24 to +370	Very high
Semiconductor Substrates						
Gallium arsenide (GaAs)	13	0.0006	Excellent	Excellent	-55 to +260	Very High
Silicon	11.9	0.0004	Excellent	Excellent	-55 to +260	High
Ferromagnetic Substrates						
Ferrite	9.0 to 16	0.001	Excellent	Excellent	-24 to +370	Medium
Synthetic Substrates						
PTFE (Teflon)	2.1	0.0004	Poor	Excellent	-27 to +260	Medium
Polypropylene	2.18	0.0003	Poor	Good	-27 to +200	Medium
Composite Material Substrates						
PTFE-glass, woven web	2.17 to 2.55	0.0009 – 0.0022	Excellent	Excellent	-27 to +260	Medium

Table 4. Potential T/R Element Substrate Materials and Properties[8]

a) T/R Module Component Analysis

Table 5 shows a list of components that can be used to build the T/R module and also the substrates that can be used for the components based on the new hybrid Microwave Integrated Circuit (MIC) / Monolithic MIC (MMIC) (microwave integrated) architecture:[8]

T/R Module Component Breakdown		
Component	**Substrate**	**Function Area**
Bipolar Transistor	Silicon based	Transmit
Pin Diode	Silicon based	Receive
Low noise amplifier (LNA)	GaAs MMICs	Transmit
Digital Attenuator	GaAs MMICs	Receive
Phase Shifter	GaAs MMICs	Receive
T/R switches	GaAs MMICs	Transmit/Receive
Microstrip circuitry	Ceramic microwave laminates	Transmit/Receive

Table 5. T/R Module Material Properties[8]

Analysis of Table 4 and Table 5 indicated that temperatures range from -55 F degrees to +260 F degrees for the semiconductor substrates and up to 1600 F degrees for ceramic substrates. These substrate materials provide excellent dimensional stability and chemical resistance.

b) Cooling Methods

There are many different methods for transferring heat from the T/R module. The optimal method depends upon the temperatures and tolerances of the application, and impact to overall system performance and supportability. Table 6 is an overview of the different cooling techniques with their advantages and disadvantages.

Cooling Method	Advantages	Disadvantages
Thermoelectric coolers	• Can be used in any orientation • Small size • No moving parts • Cooling below ambient • Temperature control • Heating capability • Compatible with heat sinks, cold plates, and heat pipes	• DC power source required • Not practical for large electronic system • Cooling density of less than 10 W/cm^2
Fans and blowers	• Low cost • Installation flexibility	• Air exchange is required; potential for dust and moisture

Cooling Method	Advantages	Disadvantages
		• Ineffective for high-power devices • Object cannot be cooled at or below ambient
Heat sinks	• Low cost • Installation flexibility	• No cooling at or below ambient • No temperature control
Liquid cold plates (passive)	• Size (at point of attachment) • Heat dissipation effectiveness	• Cannot cool below ambient (liquid) temperature • No temperature control • Potential for leaks • Liquid source availability
Heat pipes	• Reliability • Size	• Cannot cool below ambient • No temperature control
Compressor-based cooling	• Cooling large amounts of heat • Cooling below ambient • Temperature control	• Maintenance/ reliability (moving parts) • Size (units tend to be bulky) • Noise • Limited installation flexibility

Table 6. Advantages / Disadvantages for Various Cooling Methods[7, 8]

Figure 13 displays the thermal resistance per 10 cm2 from different types of cooling fluids. Natural air convection provides the highest range of thermal resistance and boiling water provides the lowest range of resistance.

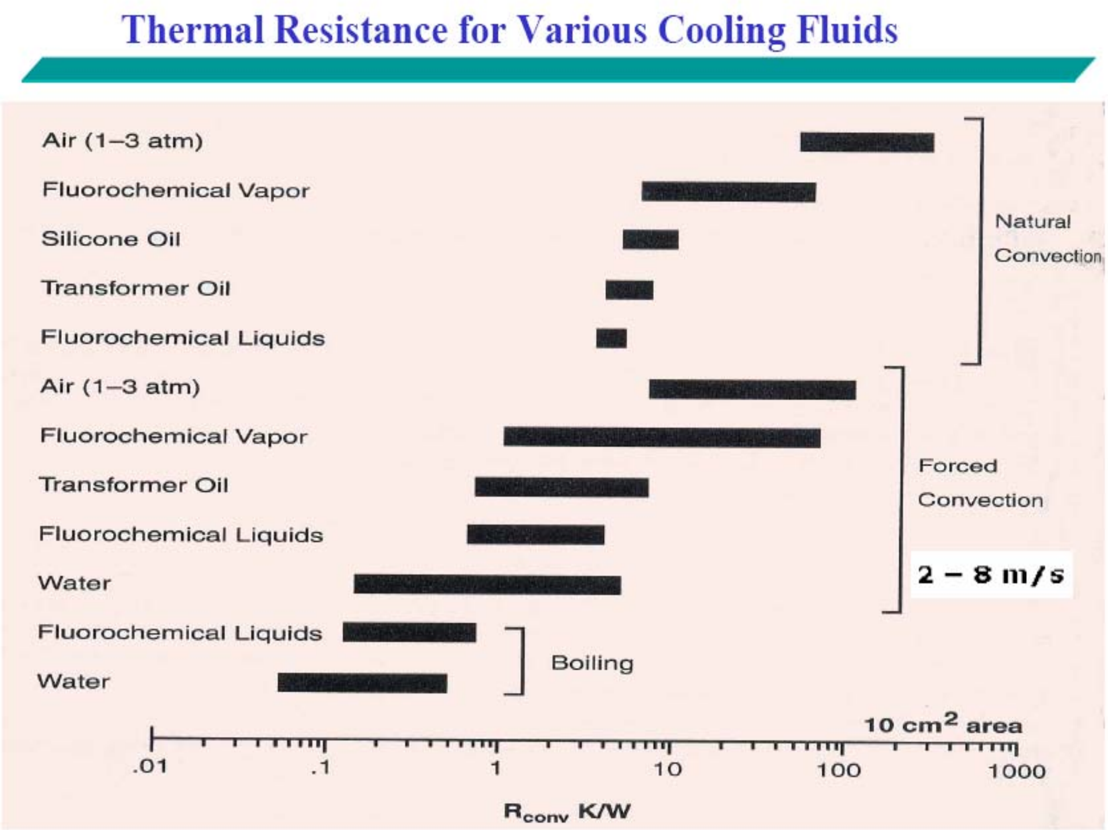

Figure 13. Thermal Resistance for Various Cooling Fluids[6]

c) Thermoelectric Cooling System

Based on analysis of the data presented, the most practical method for cooling the T/R module is the combinations of heat sinks, fans, and thermoelectric device. This combination is called a "thermoelectric cooling system." Figure 14 details the design of the thermoelectric cooling system.

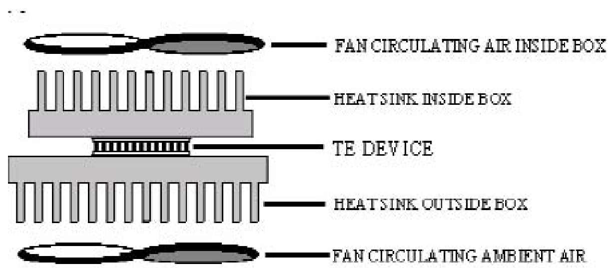

Figure 14. Thermoelectric Cooling[6]

Thermoelectrics themselves are solid-state heat pumps made from semiconductor materials[32] and have no moving parts. Thermoelectrics are manufactured in modular form, where a series of p-type and n-type semiconductor element junctions are layered between ceramic plates. At the cold junction, heat is absorbed by electrons as they pass from a low-energy level in the p-type element to a higher energy level in the n-type element. A Direct Current (DC) power supply provides the energy to move the electrons through the system. At the hot junction, energy is expelled to a heat sink as the electrons move from a high-energy element (n-type) to a lower level element (p-type). A typical thermoelectric cooling module contains as many as 127 junctions and could pump up to 120 W of heat out of the T/R module. The amount of heat pumped is proportional to the amount of current flowing through the thermoelectric enabling the possibility of tight temperature control (<0.01°C). Also, by reversing the current, a thermoelectric can be used to heat the device instead of cooling it. This is valuable when it is necessary to precisely control an object's temperature in changing ambient environments. The size of these cooling devices range from 2 to 62 mm and multiple devices can be used for greater cooling. Due to the relatively large amount of heat pumping over a small area, thermoelectrics require the addition of a heat sink and fan to dissipate the heat into the ambient environment.

For the DARBC T/R module, a thermoelectric cooling system is the most practical method for maintaining a stable operating temperature. The forced air convection in a thermoelectric system has a thermal resistance range between 8 K/W and 100 K/W per 10 cm^2 area. As shown in Figure 14, the thermoelectric device is located between two heat sinks. One heat sink is placed inside the T/R module enclosure while the other remains outside in the ambient air. As current flows through the thermoelectric,

the internal heat sink cools, allowing it to absorb heat from the enclosed air. The addition of an internal fan is recommended to circulate the air to reduce temperature gradients within the enclosure, increasing the efficiency of the thermoelectric device. The hot-side heat sink increases in temperature as the heat is absorbed from the enclosure. The ambient air absorbs the heat from the hot-side heat sink. As with the cold side, a fan on the hot side will greatly increase the performance and efficiency of the thermoelectric device. The temperature of the enclosure can be controlled through simple on-off thermostats or more precise controllers that adjust the input power to the thermoelectric depending upon T/R module temperature. In addition, condensation removal can be accomplished by using drainage ports or incorporating absorptive materials and wick structures. The small size of the thermoelectric cooler reduces the overall weight and size of the DARBC system, increasing overall system modularity likely reducing costs.

7. Search Pattern Recommendations

In order to describe where a target is located, its range (distance) and angle (direction) are required. The radar range to target is a function of the speed of light and the round trip propagation time. The angle is broken down into a horizontal component (azimuth) and a vertical component (elevation). They are measured by observing the antenna's pointing angles at the time signal detection is made, on the presumption that signals detected always originate from the direction of the antenna's beam at the time of detection.[34] Radars can differentiate between targets in various directions as well as detect targets at greater ranges. The radar's antenna concentrates the radiated energy into a narrow beam.[35]

When performing a search, the radar beam is systematically swept through a region in which targets are expected to appear. The beam's path is known as the search scan pattern. The region covered by the scan is called the scan volume or frame and the length of time the beam takes to scan the complete frame is called the frame time.

Radar systems are often identified by the type of scanning used. Scanning is the systematic movement of a radar beam in a definite pattern while searching for or tracking a target. The type and method of scanning used depends on the radar. In some cases, the

type of scan will change with the particular system mode of operation. For example the search mode scan may be quite different from that of the track mode scan.[36]

The two basic methods of beam steering are mechanical and electronic. Since the DARBC is a phased array radar, it will be electronically steered. In electronic steering, the beam is effectively moved by such means as (1) switching between a set of feeder sources, (2) varying the phasing between elements in a multi-element array, or (3) comparing the amplitude and phase differences between signals received by a multi-element array.

Since the DARBC will have the majority of its elements on the port and starboard sides of the ship, it may be necessary to orient the ship so that one side of the array is facing the desired area to scan. This will allow the maximum swing of the beam to be used, covering the largest amount of area. Positioning the ship in this way allows the maximum number of elements to contribute to the beam which minimizes the beam width increasing track accuracy.

Since the primary mission of the DARBC is to search, detect, and track ballistic missiles such as ICBMs and SLBMs, an optimal combination of search and track patterns was investigated. While searching for ICBMs and SLBMs that can "pop-up" from over the horizon or surface, a typical search radar devotes approximately one-half of its time generating what is called a "surveillance fence." The surveillance fence is normally at 3 degrees in elevation. Figure 15 and Figure 16 demonstrate the Fence Search Scan/Pattern as well as how the fence search could cue tracking of a target which breaks the plane of the fence.

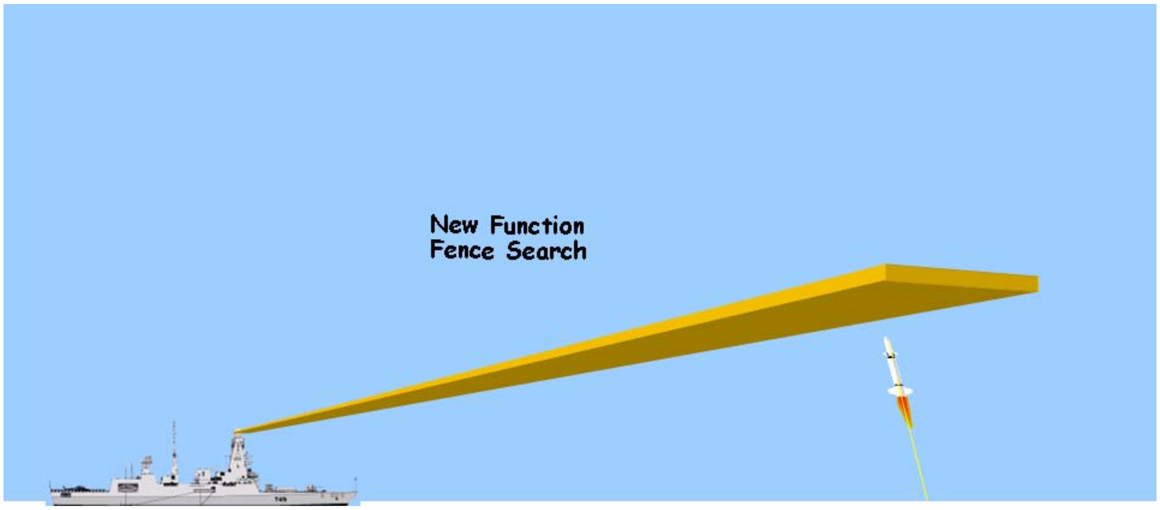

Figure 15. Fence Search

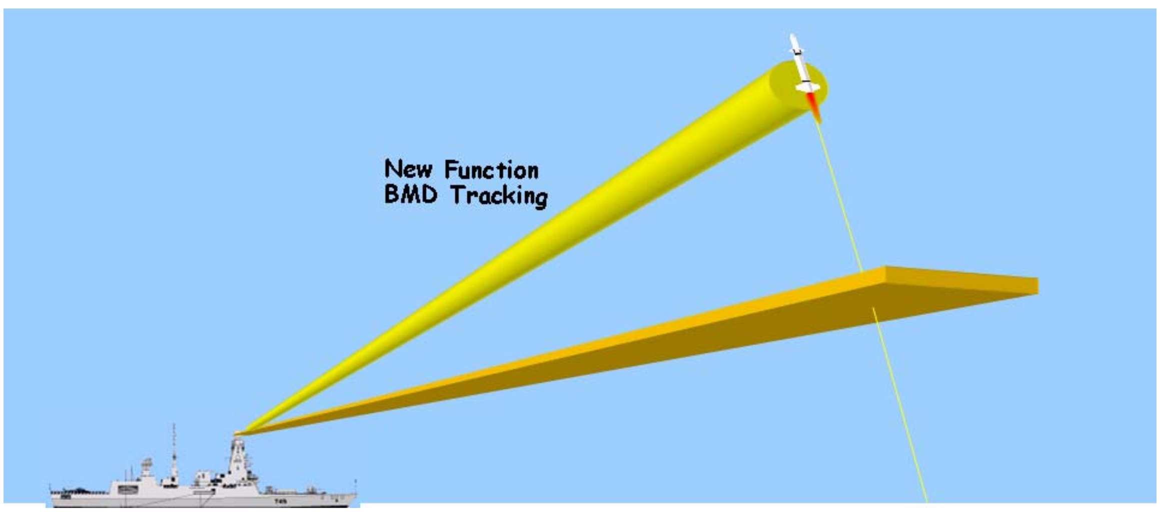

Figure 16. Fence Search Transition to Track

Fence searches work well for detecting "pop-up" targets however other search patterns are necessary for the DARBC to monitor areas above the horizon. A volume search is a 360° search pattern that covers all area around the sensor out to a defined range. This volume search is best used in the AD role where all areas of the sky should be monitored. This type of search is effective against multiple kinds of threats as long as the threat is within the volume being covered and is detectable by the radar (i.e. has a large enough RCS and is not too fast for the sensor). The downside of the volume search

is the requirement for a large amount of the radar's resources to cover the full volume, taking a relatively large amount of time to complete the search pattern compared to the fence search. Also, in order to reduce the time required to complete the search, the radar detection range is reduced in order to decrease the volume. This has an impact on long range performance which is needed for the BMD mission.

A sector search is similar to a volume search except range, bearing, and elevation windows are defined, effectively creating a volume search on a limited and defined area. The sector search can be defined in the area where hostile threats are expected to originate reducing the resources required as compared to using a volume search. With the extra available resources, it would be possible to perform one or several sector searches while also performing a fence search.

When transitioning to track, as depicted in Figure 16, conical monopulse scanning is typically initiated for this type of threat. If the target is on the scan axis while performing a conical monopulse scan, the strength of the reflected signals remains constant or changes gradually as the range changes. However, if the target is slightly off the axis, the amplitude of the reflected signals will change at the scan rate. Based on the amplitude of the reflected signal, the radar can adjust its beam direction to keep the target in the center of the scan, holding it in track. Figure 17 is a graphical representation of conical monopulse scanning.

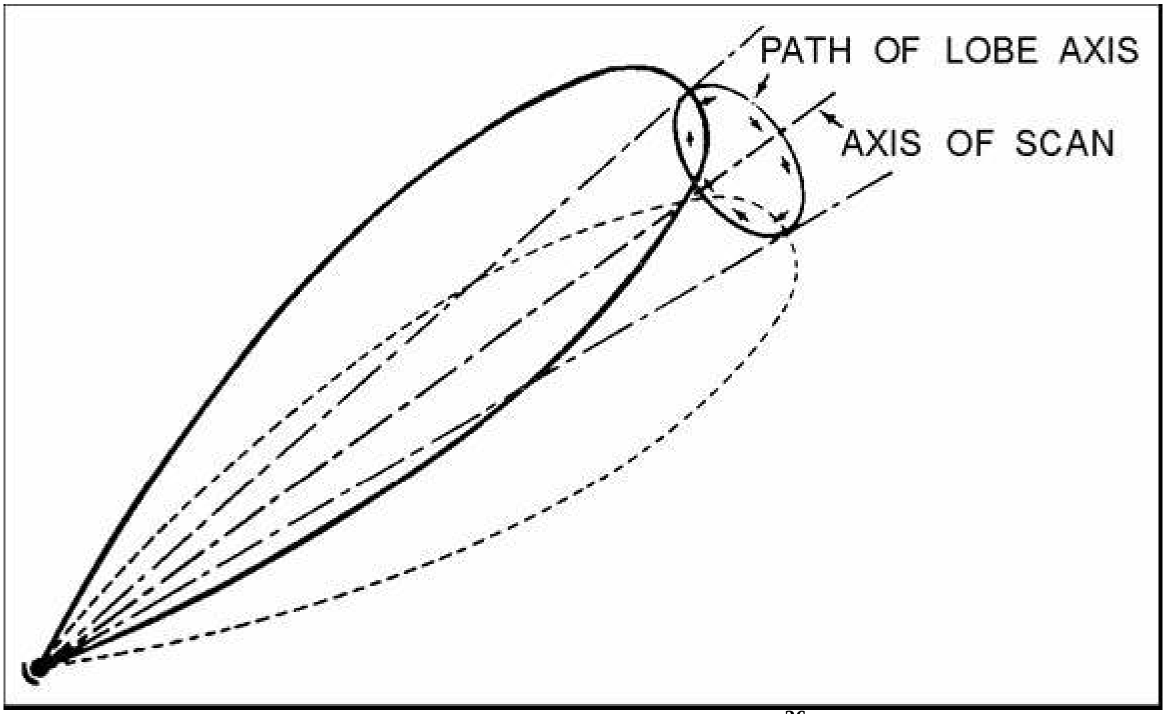

Figure 17. Conical Scanning[36]

Successful detection is a precondition for setting the entire BMD system in motion. The problem with detection is that a huge volume of space has to be covered to ensure a reliable surveillance is conducted, and this entails the implementation of special search techniques.[37] The final search pattern recommendations for the DARBC include the combination of a fence search and a sector or volume search depending on the operational scenario. Once a target is detected, transition to conical scanning is recommended to maintain track.

8. Logistics Considerations

The DARBC radar system is a significant departure from current radar design concepts and requires an evaluation of supportability concepts to avoid incurring avoidable Life Cycle Costs (LCCs) and risk areas. The DARBC system must incorporate the essential logistics support elements in order to maintain the readiness and operational capabilities that are defined in the DARBC ICD1 and CDD2. Logistics supportability factors are integral elements that must be considered while developing a support strategy that optimizes those functional operational requirements that must be achieved. In order

to ensure that a viable, cost-effective support infrastructure is planned and put into place, the RM&A of the DARBC radar system will have to be evaluated.

The logistics support element maintenance planning will be utilized to establish DARBC radar system maintenance concepts and requirements for the life of the system. The ultimate goal of maintenance planning is to determine the actions and support resource requirements necessary to maintain the design system requirements that are noted in the ICD[1] and CDD[2]. Supportability risks assessment drivers must be defined in the system analysis phase to assist in determining the maintenance concept for the DARBC system. The risk assessment should be assessed under both peacetime and wartime environments. Prototype systems and modeling will be utilized to mitigate the risks while defining the DARBC radar system maintenance concept. Logistics risk metrics for prototyping has been identified to aid in establishing a maintenance concept in the Design Interface Risk Metric (DIRM) section of the DARBC Logistics Support and Budget Requirements research study.

Acquisition logistics principle objectives have been applied to the DARBC system to ensure that support considerations are an integral part to the system's design requirements. Logistics risk metrics were performed for the DARBC system based on the key cost driver risk areas that were identified in the DARBC CDD.[2] The DARBC Logistics Support and Budget Requirements research study identifies logistics support elements that are required to ensure support considerations have been identified and are an essential part of the system's operational and supportability requirements.

9. Ship Flexure Impacts

Ships are subject to flexure due to a variety of construction, environmental and operational parameters. The DARBC has radar T/R elements dispersed throughout the ship hull and superstructure. Ship flexure can impact system performance by introducing alignment errors between elements. Traditionally these errors occur between various elements such as a fire control radar and a gun system. For the DARBC, errors introduced by ship flexure will be across T/R elements which will affect beam forming and antenna alignment. This can impact radar system performance for detection of threats and in providing accurate track information for handover to other sensors in the

BMD system network. Current weapon systems performance has not suffered as error budgets absorb ship flexure errors. Increasing ranges and capabilities of ballistic missile threats and resulting system capability requirements may not allow this in future systems like DARBC.[38] This section identifies errors and classifies them in a system error budget. It will also describe potential methods for compensation.

Ships need to flex to prevent intolerable buildup of stresses in the ship structure when subjected to operational conditions of the sea.[39] Ship flexure shows up as relative rotational motion between two points and can result in unfavorable misalignment between elements located between these two points. In traditional (current) combat system configurations this results in static or bias errors and dynamic errors between various combat system elements. These errors have been calculated and handled through system error budgets as opposed to providing a compensation to eliminate or reduce these errors. Despite being the largest error contributor, ship flexure is deemed acceptable as its impact is reduced by systems with closed loop tracking, large beam-widths of illuminators, and close-in engagements (relative to ballistic missile engagements). As engagements ranges increase from ownship, these errors can become intolerable to support functions such as handover to sensors (organic and off platform) and engagements with missile or other weapon systems. DARBC is a non-traditional sensor. As the array elements are distributed across the ship hull and superstructure, ship flexure will have a significant impact on element to element positional spacing and alignment resulting in phase differences of T/R element impacting overall system performance.

Ship flexure is generally defined as the uncompensated relative angular difference between two combat system elements from the compensated aligned state.[40] Combat system alignment is accomplished on every ship to baseline the system. This is accomplished as part of new construction and after major overall maintenance periods. Additionally alignments can be done throughout the life cycle of a ship when it is believed an error exists. Alignment is a very time consuming and labor intensive process which can be interpreted as costly and therefore undesirable to perform. Combat system alignments are performed pier side during the night or morning hours before solar heating can impact measurements. Flexure is broken down into static bias errors which occur

over a long periods (minutes to permanent) and dynamic which is constantly changing during an engagement.

a) Static Flexure Examples

1. Solar loading. The sun can dramatically impact ship flexure. If the sun is exposed to only one side of the ship as in morning or evening hours it will heat the ship and cause expansion relative to the unexposed side. Solar loading can create changes of several arc minutes between elements. The amount of solar loading and shade, material of the ship, its expansion under heating, and duration of loading all contribute to some amount of change.

2. Load-out. Ships require a great deal of material for operation including weapons, fuel, food stores, spares, personnel and associated materials. This distributed weight varies as the ship operates (consumes fuel and other material). Alignment is generally conducted when ships are loaded to 90% total weight. This requirement can be difficult to achieve as the ship may not be fully equipped at the time of alignment. Loading arrangement during alignment tests may also not reflect operational lead-out as weapons and material may need to be simulated.

3. Temperature. Similar to solar loading, air and sea temperature can have dramatic effects on ship alignment by expansion of hull materials.

4. Impact. Impact can be categorized as a permanent flex or bend to a ship caused by a load such as a large swell, impact with another ship or pier, or near explosion. When detected by an alignment test this can be measured and compensated for.

5. Steady winds.

6. Improper measurements during alignment test. Human error, test equipment error and poor procedures can contribute to a static error problem by not properly measuring baseline alignment of a ship.

b) Dynamic Flexure Examples

1. Waves. Sea state is the most common parameter describing the load that forces ship flexure. Sea state is a standard measure of wind speed, swell size

and swell period that can cause hogging and twisting moments on the ship. The length and beam of the ship, its speed and direction relative to the seas as well as its height and construction material and structure will ultimately determine susceptibility to flexure under load. A large swell of a period that introduces the most significant hogging effects is considered the worst condition.

2. Vibration. Vibration on a ship can be caused by a number of sources such as operating equipment and operational environment induced by sea state.

3. Maneuvers. Speed and rate of turns will cause torsional loads on a ship's hull.

c) Flexure Impact to Alignment and Radar Performance

Susceptibility to flexure can vary across ship class designs due to a variety of impacts. Ship design aspects such as material (Steel, aluminum, composite), construction (material thickness, support structure, open space), length, beam, weight, height, and hull type (mono-hull, catamaran, trimaran other) all contribute to the stiffness or flexibility of the ship overall or in certain locations. The further away from midships on the hull a superstructure element is located, the greater the susceptibility to flexure. Also the farther up the mast an element is located the greater the impact of flexure. The use of aperstructures needs to be considered due to the use of composites which may have different response to flexure than traditional metal hulls. No analysis is provided at this time as to whether this would have a positive or negative effect. The large dispersal of elements along the hull can exacerbate the effects of misalignment. Alignment errors will have the following two primary impacts which are depicted in Figure 18:

- T/R elements will be out of relative position resulting in phase shift errors, decreasing antenna gain and reducing performance for detection and tracking.
- Antenna alignment to ships reference will be effected causing bias errors resulting in mismatch between antenna and other sensors and possibly across sections of the antenna. This could result in lost tracks and poor handover between elements or array faces.

Dynamic flexure is usually a cyclic event and can be minimized by mathematical filters in the radar. Static flexure is an unknown bias and cannot be undone with filtering.[41] Loke discusses criteria for sensor synchronization in detail[42] and provides overall azimuth and elevation pointing error as ship does not act as a point source (gun, single phased array face, dish radar). This can be on the order of several milliradians. At 1000km, 1 milliradian error equates to a distance of approximately 300 meters. When different portions of the ship array elements provide the radiating portion of the radar, misalignment can occur as the track is handed over to other portions of the ship array elements due to ship turns and target relative position.

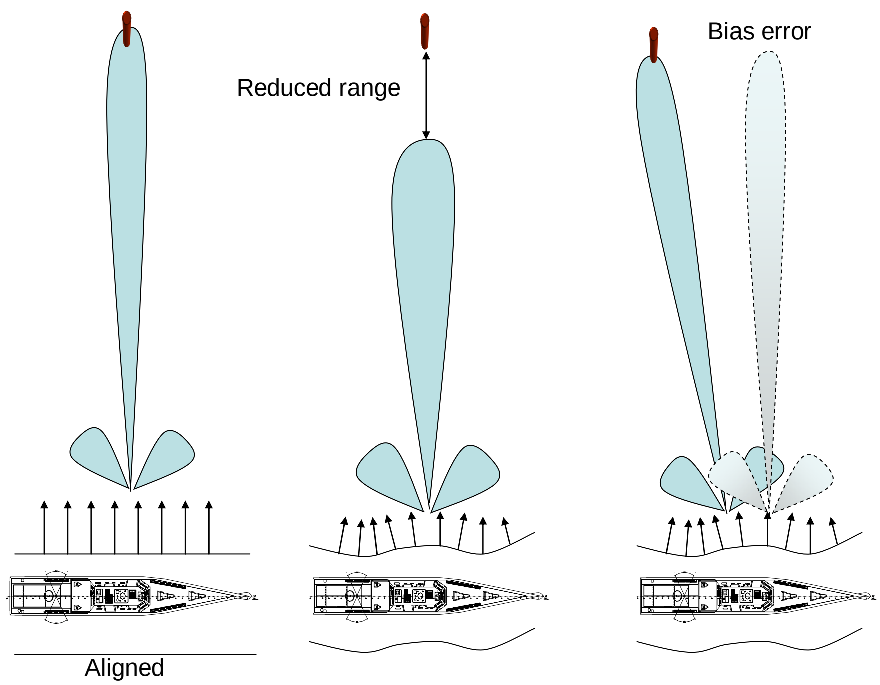

Figure 18. Ship Flexure Impact to Beam Formation and Detection Range

d) Ballistic Missile Defense Problem

The operating ranges for detection, tracking and engagement of ballistic missiles coupled with the small RCS of threats, high velocity of both threat and interceptor and need to hit-to-kill engagements allow for little error. Crossing targets make the intercept volume for a kinetic kill weapon smaller. The intercept volume is the space that the target and weapon will fill at the same time. A nose on engagement can provide a longer volume as intercept timing will be dependant on the angle of attack.

Figure 19 shows this aspect angle effect for straight on and crossing target cases. Handover between sensors on the same platform is difficult due to time synchronization errors of the two systems in addition to alignment errors. On a single platform the sensors are generally aligned to the same reference point and use the same geodesic reference. They can also be keyed to the same clock reference. Handover to a second sensor separated from the ship will increase potential for time synchronization errors and positional reference problems. Sensors can be cued and depending on the particular sensor beam-width capability, can also be directed into a search pattern to acquire the target if errors are to significant where direct cueing alone will not generate a track.

If the sensor handover is sent to an interceptor, the error budget will be determined by the onboard sensor range and resultant phase of flight. This is generally late in flight and results in a very small error budget contribution. If the handover for DARBC is to a fire control level quality/accuracy sensor, the error budget can be larger but will depend on the characteristics/performance of that sensor (or multiple sensors in the case of a network of BMD sensors).

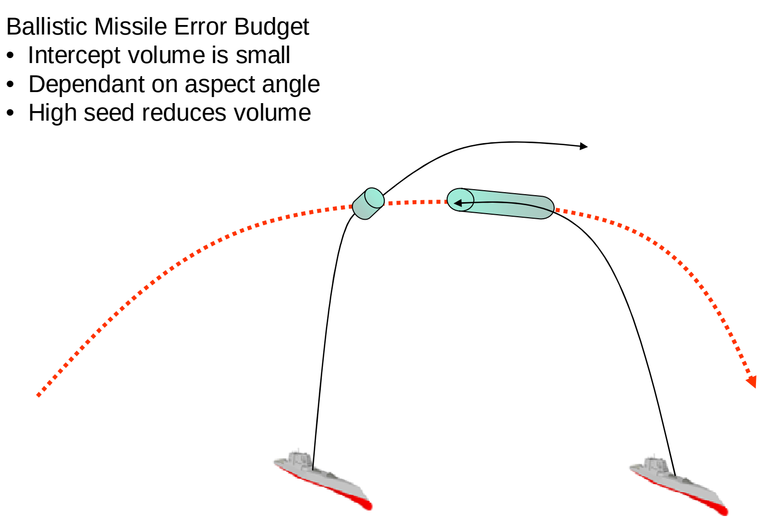

Figure 19. Head-On and Crossing Aspect Angles

e) Antenna Alignment of DARBC array

Large antenna arrays such as DARBC will naturally flex over time and require a cohering or calibration method to determine antenna element locations and provide accurate digital beam-forming. Nelson Dorney provides a description of a broadcast reference technique[43] that could be applied for the DARBC. The method measures phase of each element with respect to a number of reference beacons. Dorney also describes a self-cohering technique where one element (or possibly more) transmits conducting a self survey of the array which also applies the use of reference beacons. The uses of beacons in both the far field and near field are implied in the article[43].

Cost and time to perform a physical measurement and mechanical battery alignment of thousands of elements of an OA would be time and cost prohibitive. The capability to dynamically calibrate, while in port or on a fixed site will be required for this radar system. The use of reference beacons of known locations with respect to the DARBC ship would potentially require the development of special facilities. The entire radar would need to be visible to the beacons which may not be practical in most navy ports. The ship would need to have the ability to transmit at this facility which can also be a problem especially considering the high power levels of the system. A fixed or portable calibration system nearby naval stations is an option but would require the ship to be underway and subject to flexure effects from the sea during alignment. Also, the calibration system itself would be subject to errors that can occur in alignment tests of today. Ship flexure due to solar loading, wind loading, and temperature variations could have the similar impacts on the alignment system as on the ship. Alignment of DARBC to other sensors would also need to be considered. The beacon array would most likely operate in the VHF/UHF band. Co-locating other frequency systems and optical reference objects could allow alignment to other primary sensors. The Shipboard Electronic Systems Evaluation Facility (SESEF) utilizes the Universal Radar Moving Target Transponder (URMTT) as a supplement to aircraft services. Other Electronic Target Generators (ETG) also exist which could be used as a repeatable test tool to train ships and to help with alignment. Since SESEF facilities are land based, they are limited

in assessing elevation. Placement of ETGs such as URMTT in an aircraft would allow elevation to be assessed.

f) Dynamic Compensation

Once aligned, dynamic compensation could be provided by a number of different means. Automatic laser tracking tools exist that can measure positions of targets in 3-dimensional coordinates with high accuracy. Ships that flex can use a number of laser elements and reflectors on the hull (the targets) to measure flexure dynamically. The system would need sufficient laser systems in certain portions of the hull. Algorithms and processing are required to extrapolate flexure over large sections of the hull.

The use of differential GPS has been speculated and eliminated as an option for measuring positions of sensors.[42] Miniature ring laser gyros could be located throughout the ship to measure 3-dimensional rotation. Data from the gyro could be compared to a reference plane to determine areas of flexure. Currently ships have two gyros for redundancy to measure ships roll, pitch, and yaw. The two gyros will show different responses while ship is underway. This difference is due to ship flexure, differences in hardware alignment, or drift of electronics internal to the gyros. This fact could permit multiple gyros to be placed around key positions on the ship that represent portions of array elements.

Loke identified the potential use of a Quartz Rate Sensor (QRS) to detect angular rate motions.[42] By integrating three gyros for three axis and coupling with a clock, angular displacement can be determined similar to the gyro concept described above. They have the advantage of being small and low cost but their design was deemed not mature enough to be a viable alternative at this time.

For all these options, integration of these sensors for measuring flexure would require development of both hardware and computer software. Installation of small, low cost sensor cages at key combat system elements including DARBC array elements would be required. The software would need to collect, correlate and interpret the data from the sensors and translate into dynamic compensation adjustments.

Gyros are likely to experience gyro drift over time. One possible way to minimize drift would be to develop a hybrid system consisting of both gyros and lasers. The lasers could be used to quantify and periodically remove any bias.

Error Budget Elements	**Rough Order of Magnitude Change** **RSS= root sum squared**	**Rough Order of Magnitude Alignment Error (milliradians)**
Flexure Static	**RSS**	**39**
Temperature/sun	.5 m displacement	30
Wind loading	.3 m displacement	20
Load-out	.2 m displacement	10
Alignment test errors	n/a	5
Post alignment impact	.2 m displacement	10
Flexure Dynamic	**RSS**	**32**
Waves/maneuvers	.5 m displacement	30
Vibration	.2 m displacement	10
Time latency between sensors	**RSS**	**45**
DARBC to own ship sensor	negligible	0
DARBC to off ship Fire Control sensor	> .01 sec	45
DARBC as FC to interceptor missile		n/a
Geo Position error	**RSS**	**50**
DARBC ship to off board sensor	> 1 m displacement	50
Total Errors		**98**

Table 7. Error Budget for Ship Flexure

The operational requirements for DARBC will provide determination of overall mission requirements and capabilities. The DARBC ship, its outfitted systems, and interfaced systems to DARBC, will determine the error budget and define the capabilities the radar will be designed to. If ship flexure is determined to be too large of an error contributor, dynamic compensation will be looked at to reduce errors. Ship flexure errors may be exceeded by time latencies between platforms and position determination but will still be a significant contributor to overall error. The increased ranges and strenuous mission profiles to support BMD scenarios will likely cause tighter error budgets than today's systems. The length and distribution of DARBC array

elements will make this radar susceptible to flexure problems. Reduced detection ranges, difficulty in maintaining track, and handing over to other sensors are the likely problems caused by this flexure. No methods exist today to measure and compensate for flexure. Several technologies have potential to provide dynamic compensation but none appear to be a clear leader. Further investigation of mitigating methods is recommended. Calibrating the DARBC array will likely need to be done both pier side and underway to verify alignment and determine compensation to remove biases.

B. PROGRAM CONSIDERATIONS

1. Cost

As noted in the DARBC CDD[2] program costs and projections of LCCs are outside the scope of this capstone project. However specific system attributes have been identified by capstone team members to be key cost driver risk areas that must be addressed at the earliest stages of the acquisition cycle in order to determine if tradeoffs in performance requirements may be necessary in order to meet the criticality of the mission that the DARBC system must perform. The key anticipated cost driver risk areas that have been identified for the DARBC system are manning, reliability, maintainability, dynamic radar-ship alignment and static radar-ship alignment or calibration. The DARBC system logistics risk metric assessments analysis process considered the support resources necessary to achieve specified levels of readiness (Ao) regarding system reliability and maintainability uniqueness plus mission operating requirements. The logistics risk metrics will be utilized to determine risk handling priorities, execute risk handling plans, observe the status of risk handling actions, determine and acquire the resources necessary to execute risk management strategies. To analyze the cost driver risk areas, logistics risk metric tables were created to measure and rate program activities associated with specific critical logistics elements noted in Table 8 through Table 11. These tables identify specific logistics risk metric assessment requirements to ensure that the operational and the support characteristics for the radar will be achieved to perform its assigned mission effectively and efficiently over the life-cycle period. The Rating vs. Risk Conversion Table provides metrics for measuring and rating program activities associated with each critical logistics risk element that has been identified by capstone

team members. Each critical logistics risk element includes key program activities that identify output/performance metrics collectively to determine success or failure for a given element. The logistics risk element rating system was developed by the capstone team members based on practical knowledge and experience in the technology areas being assessed. Rating values are ranked by the following criteria:

- High (Red): Numeric rating 1.0 to 2.2. Indicates very high risk to program success due to immaturity of technology or little or no program compliance with metric identified. Risk to achieve program costs and schedule goals is high. Risk to meet threshold KPPs is high.
- Moderate (Yellow): Numeric rating 2.3 to 3.7. Indicates moderate risk to program success due to low level of maturity of technology or minimal program compliance with metric identified. Risk to achieve program costs and schedule goals is moderate. Risk to meet objective KPPs is high and threshold KPPs is moderate.
- Low (Green): Numeric rating 3.8 to 5.0. Indicates low risk to program success. Technology exists today. Risk to meet threshold KPPs is low and to meet objective KPPs is moderate to low.
- Blank (White): Numeric rating that is noted as N/A which represents that the metric is not applicable at the time of the assessment.

Rating vs. Risk Conversion	
Rating Values	**Risk Assessment**
1.0 to 2.2	High (Red)
2.3 to 3.7	Moderate (Yellow)
3.8 to 5.0	Low (Green)
N/A	Blank

Table 8. Risk Rating Levels

Manpower and Personnel		
Program Activity	**Metrics**	**Rating**
1. Maintenance Concept/Plan – includes identification of the frequency of failures for maintenance, maintenance task times, maintenance skill levels and number of maintenance personnel required. These factors are critical during the design phase to identify drivers of support and manpower requirements.	1.1 Identifies requirements for: – Special skills. – Maintenance and operator labor hours by rate by year. – Number of personnel by rate by maintenance level by year.	**2.5**
	1.2 Identifies requirements for manpower factors that impact system design utilization rates, pilot-to-seat ratios and maintenance ratios.	**2.0**
	1.3 Maintenance task times, maintenance skill levels and number of maintenance personnel required have been derived from the following: – Reliability (e.g., MTBF). – Maintainability (e.g., MTTR, maintenance task times). – Availability (e.g., task time limits). – Reliability and maintainability tests. – Performance monitoring/fault detection/fault isolation and diagnostics. – Test conducted under representative operating conditions.	**3.7**
	Activity (8.2/3)	**2.7**

Table 9. Manpower Risk Metrics

Design Interface (Reliability, Maintainability, Quality and Availability)		
Program Activity	**Metrics**	**Rating**
2.0 Reliability, Maintainability, Quality and Availability – are requirements imposed or analyses performed to insure that the system is operationally ready for use when needed, will successfully perform assigned functions, and can be operated and maintained within the scope of the logistics concept and plan.	2.1 The following measures of effectiveness or equivalent are identified in measurable quantifiable terms based on similar systems and available detail design information: – Availability. – Mean Time Between Failures (MTBF). – Mean Time To Repair (MTTR). – Frequency and duration of preventive or scheduled maintenance. – Battle damage repair capability. – Readiness thresholds for all system downtime, including scheduled maintenance.	**3.7**
	2.2 Reliability, maintainability and availability of the system are continually assessed through analyses and testing to ensure life cycle objectives will be met.	**1.0**
	2.3 Design and layout minimizes unnecessary removal of items to gain access for maintenance and minimizes design of special tools.	**1.0**
	2.4 Maintainability predictions and task time analyses are completed for organizational level or shipboard maintenance as a minimum.	**4.0**
	2.5 Mock-ups, prototypes and/or simulations to assess accessibility are completed as part of design.	**1.0**
	2.6 Accessibility and maintainability are validated through tests.	**1.0**
	2.7 A quality program is established to assure implementation of design requirements into process control characteristics.	**1.0**
	Activity(12.7/7)	**1.8**

Table 10. Design Interface Metrics

Dynamic/Static Radar-Ship Alignment or Calibration		
Program Activity	**Metrics**	**Rating**
3.0 Maintenance Plan to repair or calibrate antenna elements – includes documentation of the Support Equipment (SE) concept as a result of the level of repair analysis, organic repair/contractor (OEM) support and the sparing concept.	3.1 Establishes the diagnostics concept to test the antenna elements.	**1.0**
	3.2 Identifies test and fault isolation capabilities desired of automatic, semi-automatic and manual test equipment at all maintenance levels, expressed in terms of realistic and affordable probabilities and confidence levels to repair or calibrate antenna elements.	**1.0**
	3.3 Identifies the SE associated with the most economical level of repair (usually determined in the level of repair analysis) unless over-ridden because of non-economic factors.	**1.0**
	3.4 Identifies manpower, training and maintenance task requirements.	**1.0**
	3.5 Identifies required technical documentation to support the SE.	**1.0**
	3.6 Identifies the level of maintenance at which the various SE is required to repair or calibrate antenna elements (e.g., organizational, intermediate and depot level maintenance).	**1.0**
	3.7 Types and quantity of SE for each location has been established.	**1.0**
	3.8 Calibration requirements are specified.	**1.0**
	3.9 Support Equipment Requirements Document is submitted by the contractor to justify SE requirements and initiate follow-on support activities.	**1.0**
	Activity(9/9)	**1.0**

Table 11. Radar Alignment Risk

2. Strategies for Future Development and Evaluation (SEP)

Once the Full Rate Production (FRP) of the DARBC system is authorized, a long term buy of the system components (especially, T/R modules) should be funded by the program office and managed by Naval Inventory Control Point (NAVICP). This helps reduce price creep due to part obsolescence and lack of qualified vendors bidding on component request for bids. Also, organic depots should be included from the DARBC

program initiation by the program office for intermediate and depot level work, rather than relying solely on the OEM for non-organizational level work. This competition will keep operation costs in check.

The DARBC system is intended for operation in forward deployed areas. There is a very good possibility that the DARBC will operate in an EW intensive environment. Future DARBC design considerations should be given to this possibility.

When possible, open-architecture shall be used in the DARBC system design. Utilizing digital architecture lends itself to advanced signal processing. The use of open architecture allows DARBC system signal processing to change as advances in state of the art technologies evolve. Design considerations that should be emphasized are frequency agility, jitter and stagger. Another DARBC system design consideration is single site control of multiple DARBC systems or system components (e.g. OA antenna, transmitters) for bistatic or multi-static operation.

A design feature for DARBC system development consideration is integration into FORCENet. Although this integration goes without saying for any future major weapons procurement, its importance is emphasized by stating it. Also, integration with USN Link 16 and 11 should be a requirement for additional design considerations, as well as similar US Army and Air Force systems. Integration with future space based radars should be considered as a DARBC system design requirement also.

Design considerations should be given to a variant of the DARBC system that is less expensive. This variant could be used by Military Sealift Command, Foreign Military Sales (FMS) or North American Treaty Organization (NATO) ships to cue USN DARBC systems or link to a joint data network.

Development of a Systems Engineering Plan (SEP) should be considered to help identify program risk areas. This SEP could also identify development strategies including a detailed prototype, a Test and Evaluation Master Plan (TEMP), procurement strategy, supportability concepts and detailed ship integration concepts including development of the aperstructure into superstructure and hull forms.

3. DOTLMPF

The policy considerations for the Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) associated with fielding the DARBC are addressed at a high level in this document. The doctrine for the DARBC includes publications, tactics, techniques, and procedures on how the radar will function on its own and in a System-of-Systems (SoS) environment. This doctrine will guide the way the military utilizes the DARBC system. Doctrine will be heavily influenced by the overall mission of the DARBC ship and associated weapons systems. A forward deployed DARBC tasked to engage ballistic missiles over a threat nation will apply a different set of rules of engagement than a homeland defense positioned ship.

The organizational reporting structure for the DARBC platform will be influenced by other platforms that may be operating in conjunction. A DARBC ship positioned for early detection of launch supporting engagement from other platforms will need an organization structure that supports ship positioning and launch considerations in addition to a system that can pass track information. DARBC search areas can be optimized if threat sectors and types are known. Timely reporting of this intelligence information through the organizational elements is required to ensure effective use by DARBC to accomplish its mission.

DARBC training will be documented by a Navy Training System Plan (NTSP) and will cover all elements of instructor requirements, shipboard operator and maintainer courses, remote maintenance support personnel, and all hands on training including embedded training capabilities.

DARBC will apply COTS equipment, military developed equipment, and Non-Developmental Items (NDIs) to minimize development and procurement costs. Application of these items needs to consider LCC and ability to meet key system capabilities such as reliability. Significant materiel costs and timing will be associated with the development and procurement of the DARBC ship platform.

The requirement for minimal manning will depend largely on availability of qualified personnel. The competencies, skills, and abilities of personnel must be

established and known and be considered as a driver for design decisions. DARBC personnel requirements will consider all levels of operations and maintenance including shipboard, remote maintenance, Fault Detection Fault Isolation (FDFI) and depot.

Facilities for DARBC need to ensure infrastructure capabilities to meet unique design aspects of DARBC. The integrated hull structure of DARBC may impact ability of tug or Underway Replenishment (UNREP) platforms to approach and interface with the ship in order to not damage array elements. Calibration and alignment of the array elements may require unique design features at piers to allow direct visibility to antenna elements during radiation. Remote maintenance facilities will require bandwidth, trained personnel, and representative systems to assist in troubleshooting and repair recommendations so ships force is seamlessly supported at all times. Pier facilities will need to be able to support DARBC such that aperstructures are not damaged.

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IV. MODELING EFFORTS

A. RADAR CROSS SECTION (RCS) MODELING

Initially, it was assumed that a normal (90° aspect angle) RCS should be used for a notional ballistic missile target because the DARBC will most likely detect a ballistic missile shortly after launch during boost and ascent phases of flight, leaving the orientation of the target to be nearly perpendicular to the radar beam. An initial RCS model was generated using Microsoft ® Excel which calculated a normal RCS for a simple cylindrical object. As threat representative inputs were entered into the model, the output was observed to be several orders of magnitude higher than expected.

A ballistic missile RCS was initially assumed to be $10m^2$ for all frequency bands. Upon further research, this value was confirmed by reviewing a table relating different objects from birds to planes to their respective RCSs. This table also brought to attention that the RCS will vary with frequency[44]. The values on the table generally used S-band or X-band frequencies. The assumption was refined that the RCS of $10m^2$ would be for S-band only and RCS values in the VHF and UHF bands would be calculated.

Following the initial RCS calculations in Excel®, a MATLAB® model analysis tool was used to generate mathematical algorithms to calculate the RCS for a cylinder to more accurately simulate the ballistic missile target. The normal and non-normal incidence backscattered RCSs for a finite length, finite radius cylinder (see Figure 20 and Equations 4.1 and 4.2) are given by the following equations:

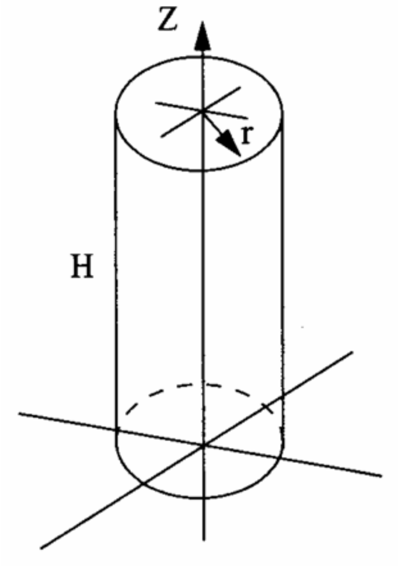

Figure 20. RCS for Cylindrical Reflector[45]

$$\sigma_n = \frac{2\pi H^2 r}{\lambda}$$ **,** for broadside 90 degree backscatter 4.1

$$\sigma = \frac{\lambda r \sin\theta}{8\pi(\cos\theta)^2}$$, for different aspect angle backscatter 4.2

Typically there is relative motion between the radar and observed target. This implies that the observed RCS measured by the radar fluctuates over time as a function of frequency and target aspect angle. This observed RCS is referred to as the dynamic cross section or dynamic RCS[45].

Normalized target dimensions of two meters for the radius and 18 meters for the height were used to simulate a ballistic missile target. In order to get a RCS value in square meters, apply the radius and height values for the normal (90° aspect angle) RCS calculation to the non-normal aspect angle backscatter calculation. The calculated RCS value is then converted to dbsm and plotted against the aspect angle for VHF, UHF, and S-band frequencies. This analysis was done to determine at which aspect angle, the notional ballistic missile target would have a 10m^2 RCS in the S-band. Also, similar plots were generated which identified the aspect angles that would let the same size target

have a $10m^2$ RCS in the VHF and UHF bands. This was done as a sanity check on our analysis. Figure 21, Figure 22, and Figure 23 contain the simulation graphical results from the MATLAB model analysis tool:

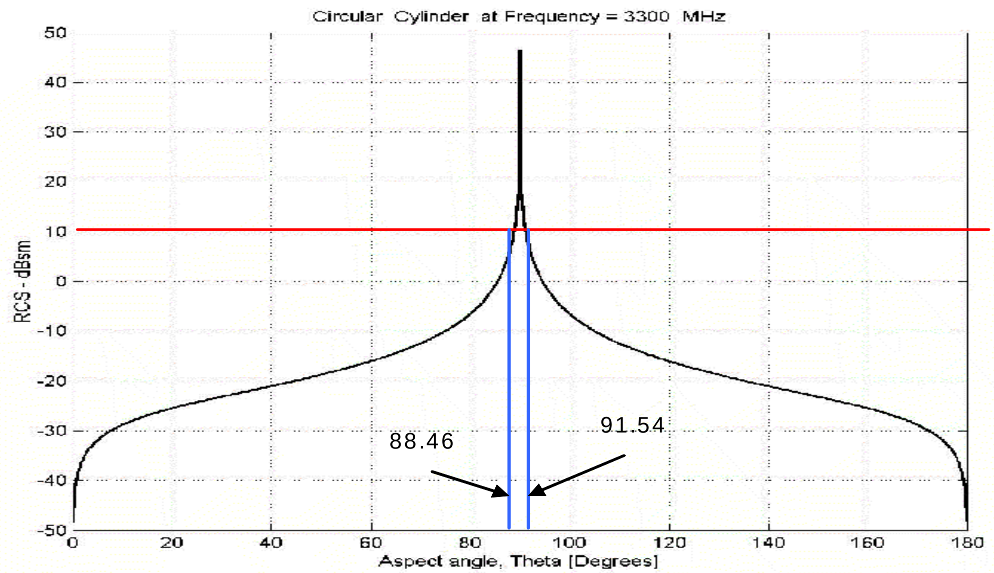

Figure 21. RCS as a Function of Aspect Angle for S-Band

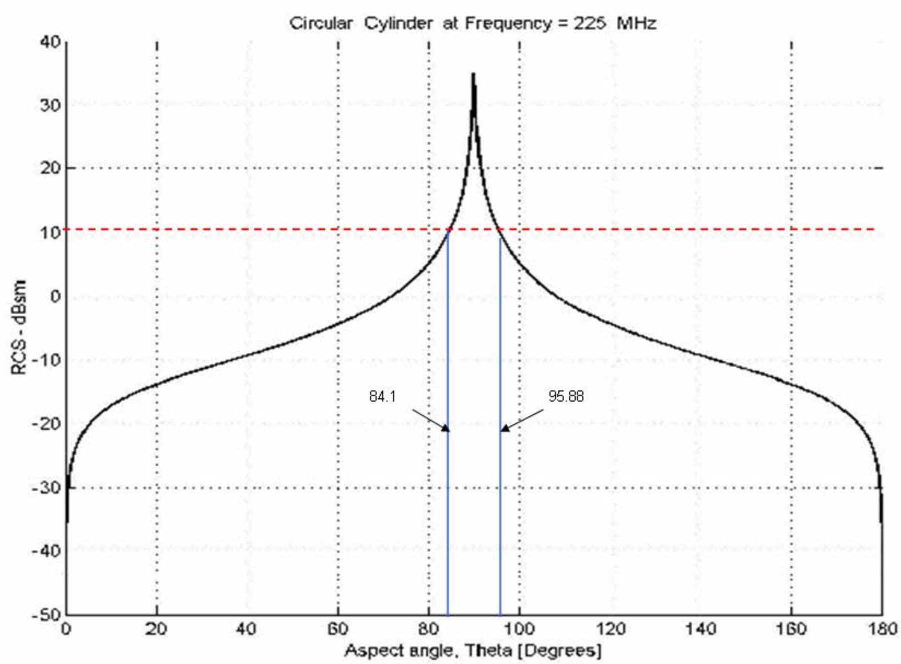

Figure 22. RCS as a Function of Aspect Angle for VHF

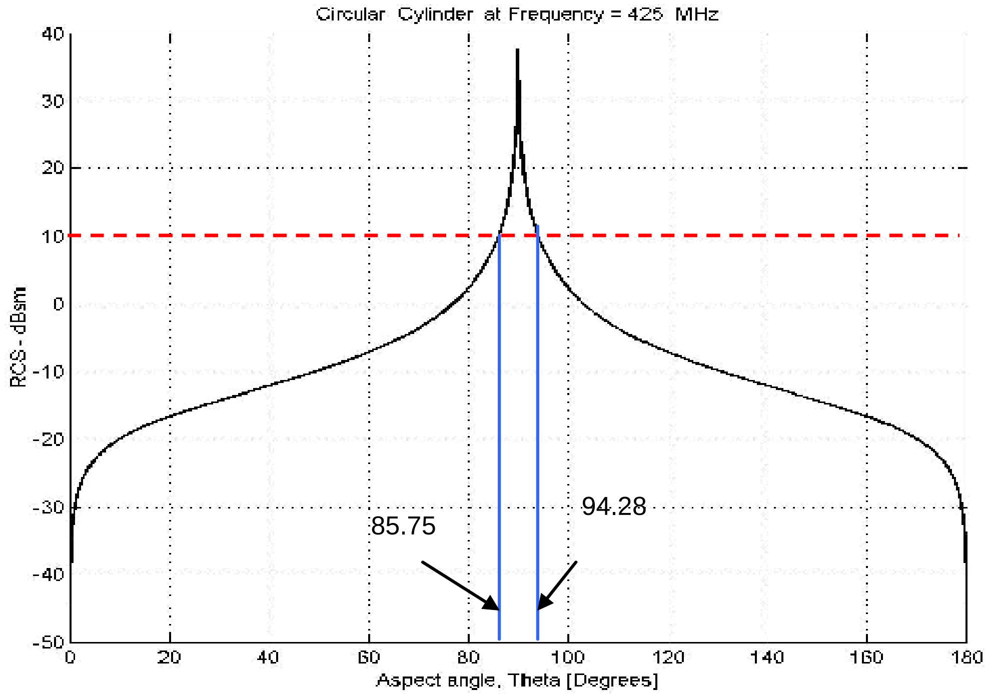

Figure 23. RCS as a Function of Aspect Angle for UHF

The figures show that in order to maintain a RCS $10m^2$ in the S-band, an aspect angle of 88.46 or 91.54 degrees is required. This is a near normal aspect angle which satisfies all initial assumptions. Using the same aspect angle of 88.46 degrees in the VHF and UHF spectrums, new RCS values were calculated using the dimensions of a notional ballistic missile. Using these values, RCSs of $77m^2$ and $146m^2$, for the UHF and VHF frequencies, respectively, were obtained. In conclusion, the analysis output was that the RCSs of $77m^2$ for UHF and $146m^2$ for VHF using a fixed, near normal aspect angle of 88.46 degrees were used for a notional ballistic missile. These values were used in the radar technical parameters research.

B. RADAR PERFORMANCE MODEL

Waterloo Maple ® 7 was used to derive the technical requirements for the DARBC. With this software, the radar equation and other equations were used as described in section III.A.2. All the parameters in of section III.A.2 have their corresponding Maple variable names which can be traced to the Maple Radar

Performance Model Source Code located in Appendix B. To use this model, the variables were assigned values which were input by the user based on assumptions, references, research, or calculations. After all the variables had values assigned, all commands in the Maple file are executed in order (from top to bottom). Near the bottom of the Maple worksheet, several plot commands generate the output plots which are seen in section III.A.2. The radar parameter values were ultimately obtained by using this model in a trial and error fashion. Radar parameters were checked to ensure all inputs to the model would be feasible in the real system. Inputs were manually varied in an attempt to characterize how each input affected the results. DARBC system KPPs were met using the parameter values in Table 1 of section III.A.2, but further sensitivity studies were conducted to show how modifications to inputs, such as the number of elements, power, and gain affect the output. These sensitivity plots were done on variant worksheets of the original Maple model and their source code is included in Appendix B.

C. REACTION TIME ANALYSIS ONE SHIP TWO SENSOR SCENARIO

In this Microsoft Excel ® model the subject ship is, in all cases, equipped with a weapon system. The weapon's range exceeds the tracking range of the WCS. The WCS has two track range parameters. The first, Un-aided R_D, is the range at which the unaided WCS can detect, acquire, and track a TBM. The second range, Aided R_D, is achieved when the WCS receives a cue or designation from another source, the DARBC in this case. For this investigation the ranges of our notional WCS are Un-aided R_D = 300 km, and Aided R_D = 748 km. The DARBC detection range is assumed to be 2000 km.

The calculations are based on some assumptions supported by a Congressional Budget Office study[46]. According to the study a typical TBM burnout velocity ranges from 6 to 7 km/sec. Because the study is two years old and the DARBC is a future system, 7.5 km/sec is used. As shown in the CDD, the ranges of TBMs are up to 1000 km for a SRBM, between 1000 and 3000 km for a MRBM, between 3000 and 5500 km for an IRBM. Again high range values of 1000, 3000, and 5500 and apogee values of 160, 500, and 900 km are used to compensate for future advances in TBM design.

Flight path calculations can be complex. They can be based on a rotating, oblate earth with a four-thirds aspect ratio. However, this model is based on a flat, non-rotating earth. The Equation 4.3 is used for the flight path of a TBM is elliptical in the form:

$$y = Y_c + b\sqrt{1 - \frac{(x - X_c)^2}{a^2}} \qquad 4.3$$

<u>VALUES</u>

x is the horizontal (range) axis.

y is the vertical (altitude) axis.

Yc is the vertical center of the flight path ellipse in kilometers from the ship due to the curvature of the earth (assigned 0 in this analysis).

Ship is always at x = 0, y = 0.

<u>ADJUSTABLE VARIABLES</u>

Xc is the horizontal center of the flight path ellipse in kilometers from the ship.

a is the semi-major (horizontal) axis of the ellipse in km.

b is the semi-minor (vertical) axis of the ellipse in km.

R is the radius of the earth in km.

The horizontal range of each TBM is divided into 1000 segments. The length of the chord across each segment's flight path is calculated and assumed to be a good estimate of the length of the flight path arc. Next the chord length is divided by the TBM velocity to determine the time taken to travel that segment of the flight path, and to maintain a running total flight time. The range is then calculated using the x and y coordinates of the end of the segment, which is then used to calculate the change in range for that segment. Total time for each of the three range-spaces was calculated as a sum of the segment times for applicable flight path segments.

The following criteria were used to determine if a segment's flight path was applicable to a range-space.

- Range-Space #1: 0 km out to the Unaided R_D
    - The segment ends within the range-space, or,
    - Both
        - The segment ends in range-space #2 on the outbound leg, and,
        - The range-space #1 time is greater than 0
- Range-Space #2: Unaided R_D out to the Aided R_D
    - The segment ends within the range-space, and
    - Either
        - The segment ends in range-space #2 on the inbound leg, or,
        - The range-space #1 time is equal to 0
- Range-Space #3: Aided R_D out to the DARBC R_D
    - The segment ends in range-space #3 on the inbound leg

If a target has been in range-space #1, the WCS is already tracking it and is capable of maintaining that track out to Aided R_D. The unaided WCS is not capable of acquiring a target in range-space #2. So, if the target has not yet entered range-space #1, acquiring it with the WCS is only possible if the WCS is aided by the DARBC. An outbound target in range-space #3 is un-engagable.

This model does not account for the acceleration of the TBM. It is assumed to be at full speed immediately after launch. This assumption makes the analysis much simpler and the errors it induces are of smaller magnitude than those that result, or would result from uncertainty about velocity and acceleration values and launch angle. This assumption also leads the results of this analysis to be more conservative, i.e., if the target initial velocity was zero and it accelerated to full speed at some later time, the time-benefit from the DARBC would be greater.

Because the objective of this analysis was to identify engagability gains attributable to the DARBC, the analysis only considered TBMs that could be engaged, i.e., those with launch ranges for which the flight path at least entered the Aided R_D. The Excel analysis tool allows the boost phase duration to be set as a percentage of the total flight time. For this analysis, boost phase duration was set at 25% and flight paths are only analyzed from launch to the end of boost phase because the DARBC's main goal is to support boost phase intercepts. Figure 24 through Figure 26 are representative of the three important types of results from this model: extended engagement time, the ability to engage a previously un-engagable target, and additional evaluation/preparation time.

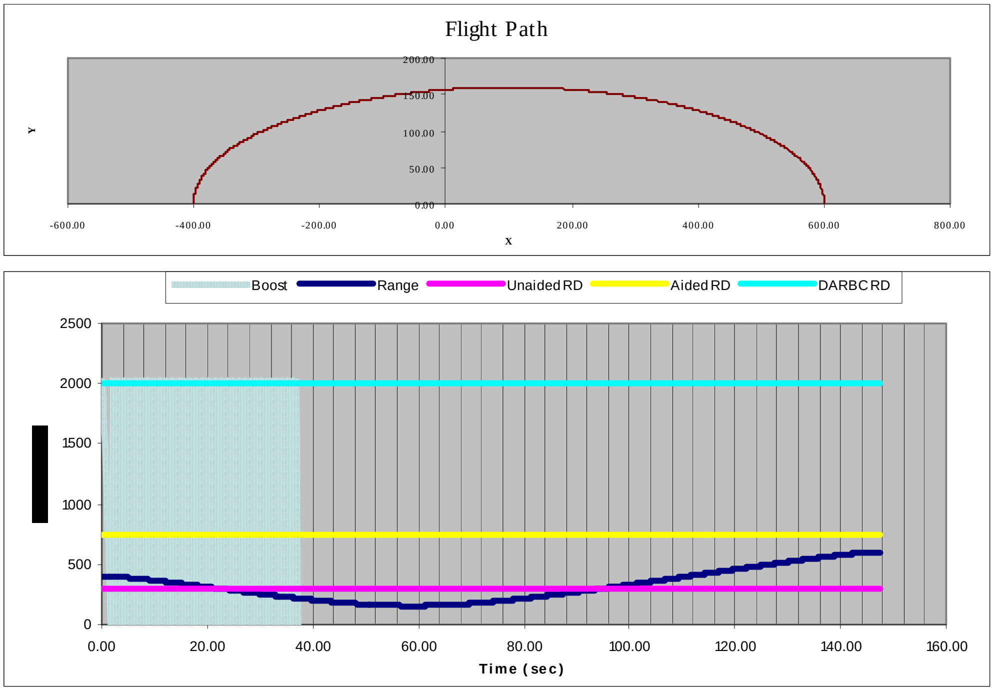

Figure 24. SRBM Flight Path and Time-Range Plot (400 km launch range)

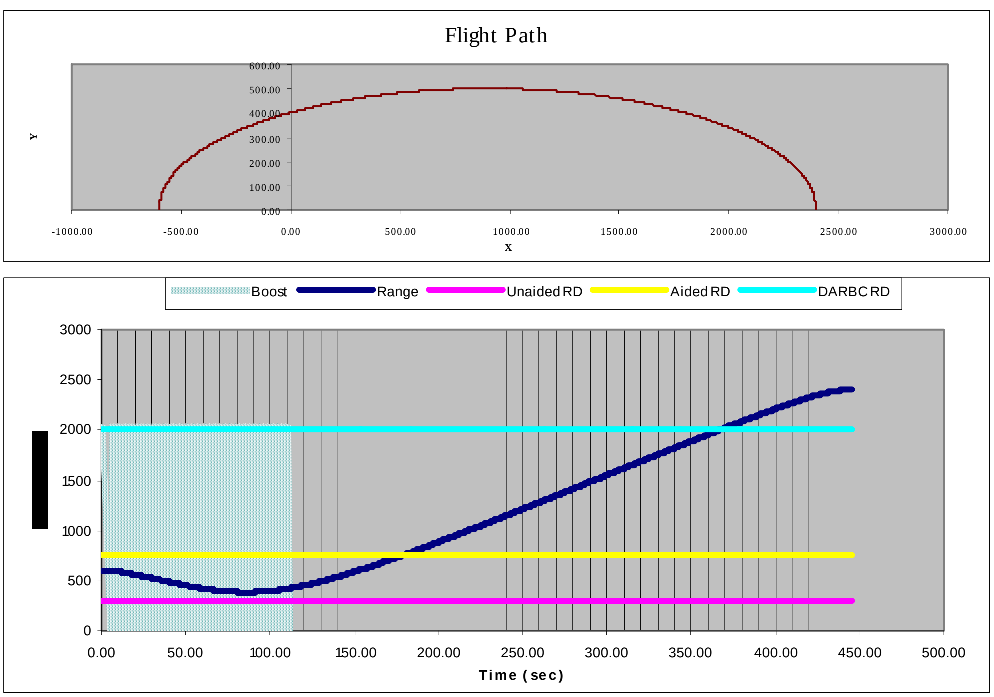

Figure 25. MRBM Flight Path and Time-Range Plot (600 km launch range)

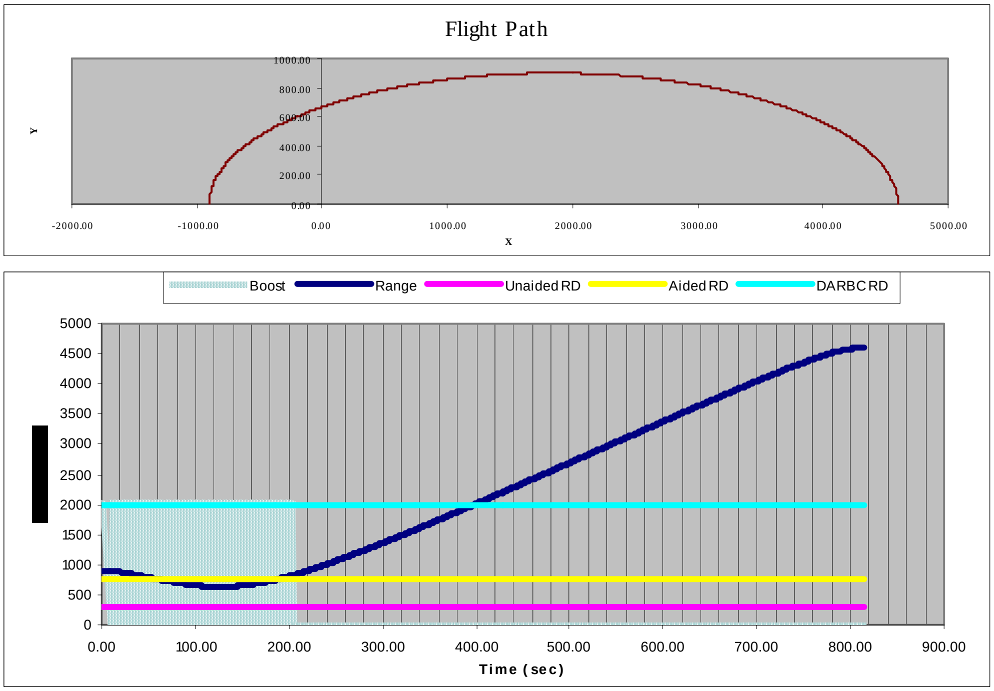

Figure 26. IRBM Flight Path and Time-Range Plot (900 km launch range)

Figure 27 through Figure 29 are based on further analysis of the model's time-range plots. Each plot shows the times in each range-space, stacked, i.e., showing the additional time afforded by each range-space. The area under the Unaided-t line shows launch ranges that would be engagable by an isolated WCS and how long a target would be engagable. The area between the Unaided-t and the Aided-t lines shows the launch ranges that would be engagable by a WCS when cued by the DARBC and duration of that engagability. The area between the Aided-t and DARBC-t lines shows how much extra time would be available to evaluate a target with a given launch range. They also show improvement in the launch range coverage as the horizontal distance between the point before reaching zero on the Unaided-t line and the Aided-t line. The span of launch ranges shown begins at 0 km and ends at the smallest launch range that presents 0 engagability time.

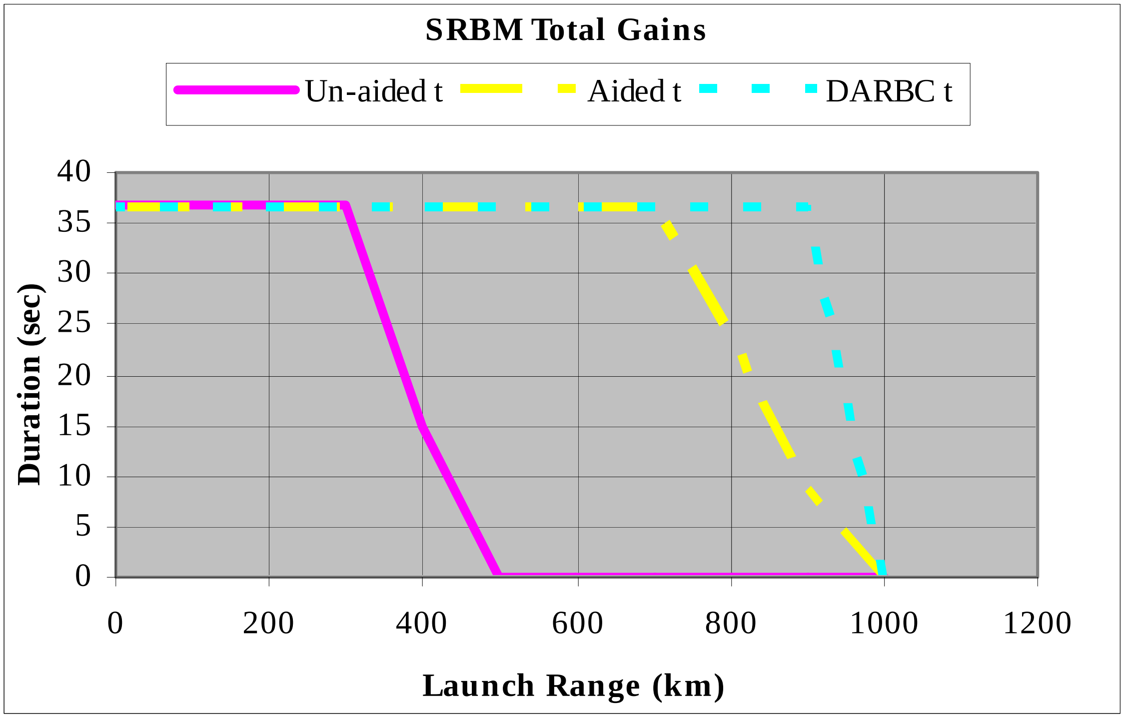

Figure 27. DARBC Gains Against SRBM

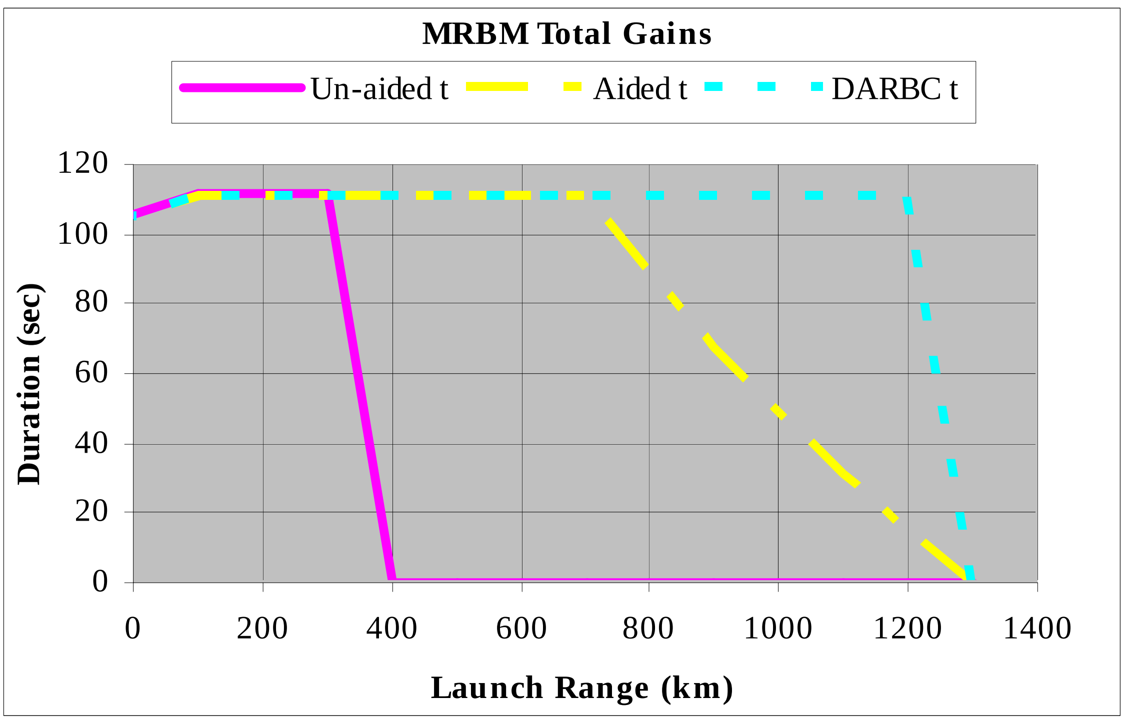

Figure 28. DARBC Gains Against MRBM

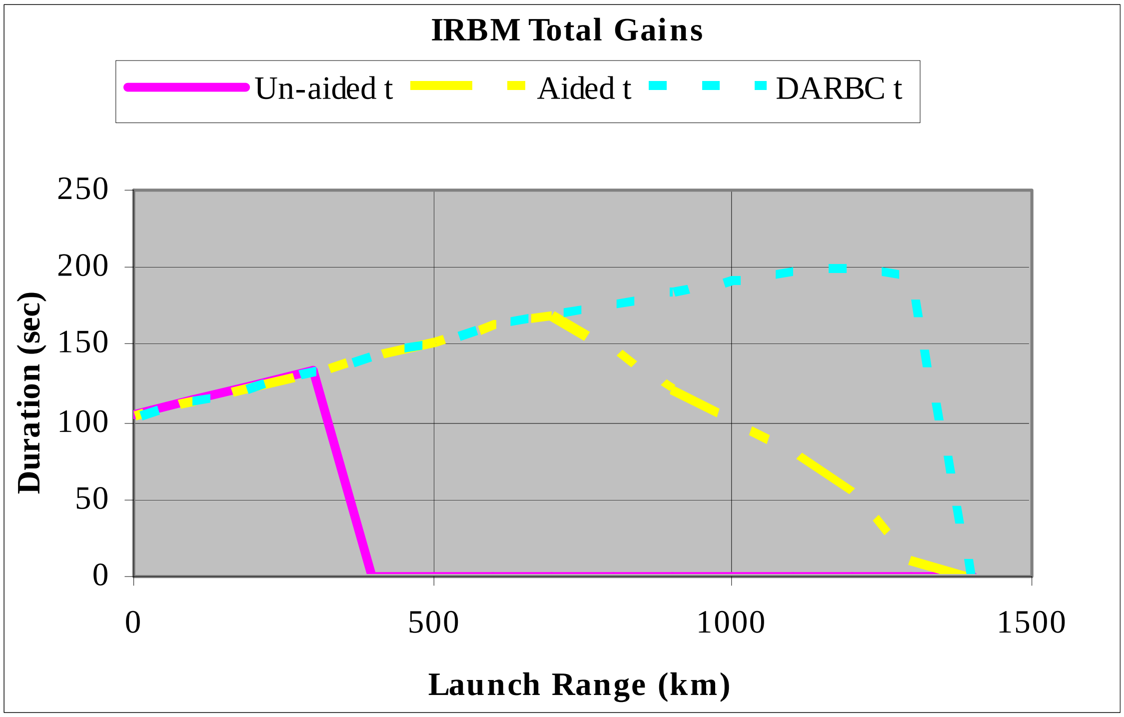

Figure 29. DARBC Gains Against IRBM

DARBC would provide the generic benefits of having an additional sensor available, increasing the overall probability of detection. That would allow the time resources of the WCS to be re-prioritized. Using only a handoff to an organic weapon system, the DARBC also shows the following benefits.

- Against the SRBM, the DARBC provides:
  - up to 22 seconds of additional engagement time at a launch range of 400 km,
  - up to 28 seconds of additional evaluation time at a launch range of 900 km,
  - increased coverage from 400 km to 900 km launch range.
- Against the MRBM, the DARBC provides:
  - up to 96 seconds of additional evaluation time at a launch range of 1200 km,
  - increased coverage from 300 km to 1200 km launch range.

o

- Against the IRBM, the DARBC provides:
    - o up to 182 seconds of additional evaluation time at a launch range of 1300 km,
    - o increased coverage from 300 km to 1300 km launch range.

D. REACTION TIME ANALYSIS TWO SHIP TWO SENSOR SCENARIO

A stochastic reaction time model using the Arena ® 10 process simulation software was used to model system reaction time for the case of DARBC operating in conjunction with another S-band configured ship in a detect through engage sequence. The model was built with two baselines. The first one with the DARBC cueing to an S-band radar. The second was the S-band radar operating unaided. Both baselines had targets with uniformly distributed ranges, RCSs, and velocities as seen in Table 12.

Parameter	Minimum	Maximum
RCS	$1m^2$	$300m^2$
Target Speed	1 km/s	10 km/s
Range from Ownship (DARBC aided)	500 km	5000km
Range from Ownship (local sensor only)	50 km	300km

Table 12 Arena Model Parameters

Also assumed in these baselines is that the target velocity is the closing velocity with respect to the ship. Initial detection time was collected based on a process simulation. For the baseline with the DARBC, if the target was generated at a position outside the maximum range of the DARBC (assumed to be 2000 km) then the target would not be detected until it closed to within that range limit and the detection time process was complete. If the target was generated inside the detection range, the detection time was assumed to be time of completion of the detection time process. If the

target RCS was less than that of the notional ballistic missile, then the target was not detected. As the target closed on the handoff range, an engagement process simulation occurred which considered target acquisition, time to establish a fire control track, identify the target, compute the firing solution, grant permission to launch a missile, process launch sequence, and launch the missile. Missile flight time was not included in this sequence. The total time from initial detection to the time of missile launch was measured during each run and over an average of 10 runs. This was done for both baselines.

This model included a very simplistic 1 degree of freedom target flight path of a radially inbound ballistic missile. Reaction times were 16.2 seconds for the model with DARBC and 10.5 seconds without. The results showed that on average, the system with the DARBC had approximately 53.5% more time to engage the target than the system without the DARBC.

The reaction time model baseline representing the scenario with DARBC operating with an S-band ship is described by Figure 30. In the second scenario, described by Figure 31. the S-band ship operates independently without the benefit of designations from DARBC.

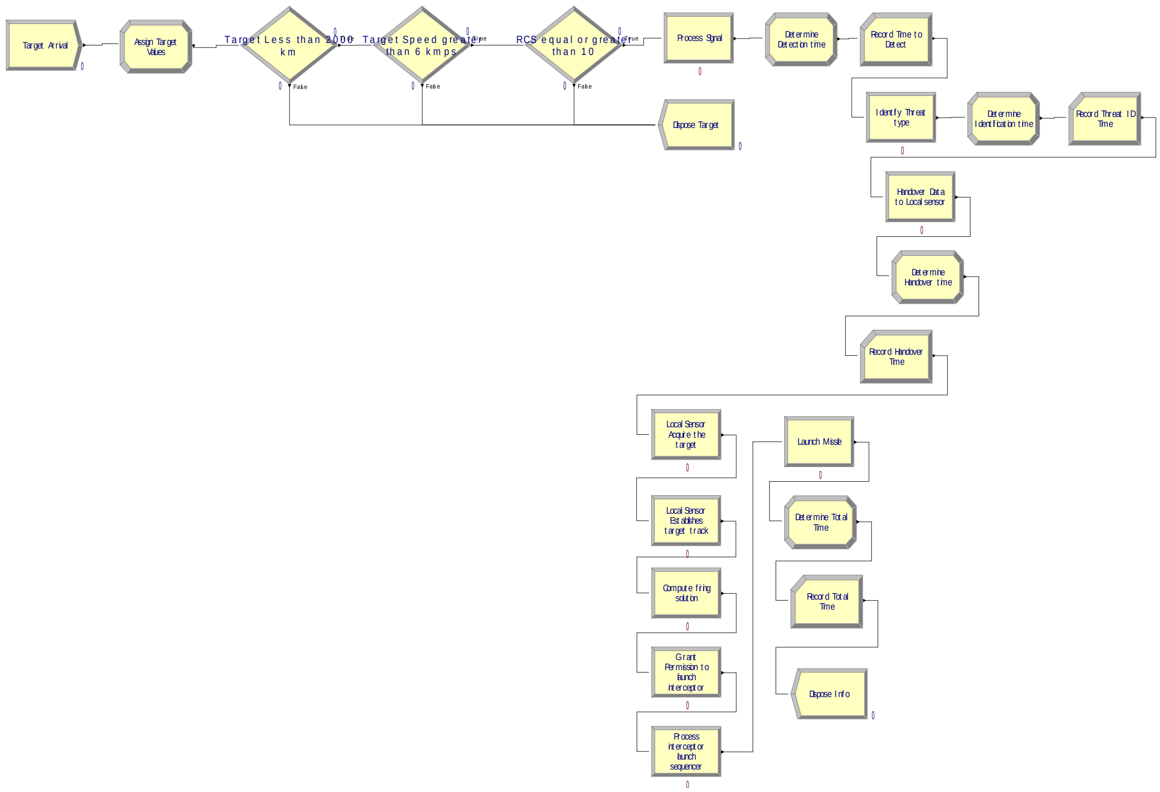

Figure 30. Arena Model 1: DARBC Designates to Remote S-Band Ship

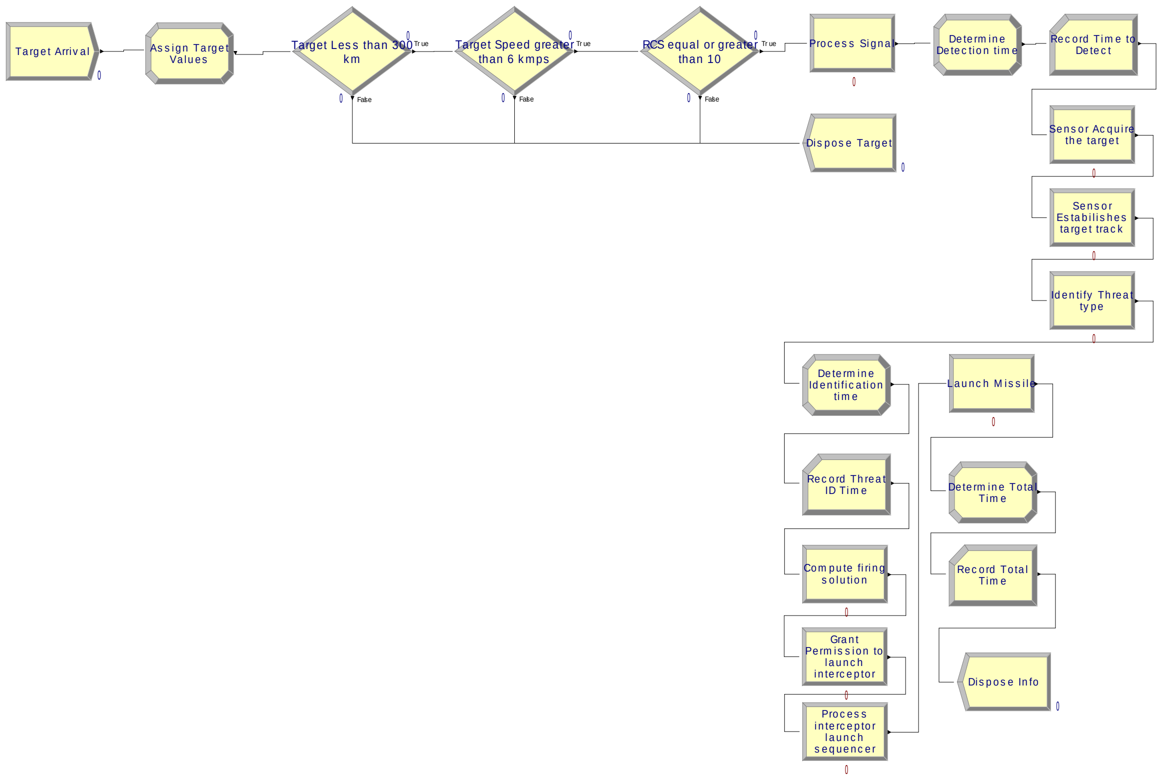

Figure 31. Arena Model 2: S-Band Ship Operates Independently

The following attributes were used to model the reaction time in Arena:

Frequency: VHF (216–225 MHz), UHF (420–450 MHz), S-band (3.3 GHz)

Arrival Time: TNOW

RCS: Uniformly Distributed, 1 to 300 m^2

Target Speed: Uniformly Distributed, 1 to 10 km/sec

Target Range: Uniformly Distributed, 500 to 5000 km (DARBC aided)

Target Range: Uniformly Distributed, 50 to 300 km (Local Sensor only)

Table 13 and Table 14 show the analysis results from the models:

DARBC Radar Aiding Local Sensor	Average (sec)	Minimum Value (sec)	Maximum Value (sec)
Record Time to Detect	1.4573664	1.0087536	1.983207
Record Handover Time	5.652	0.629757	9.99
Local System Engagement Time	9.0906336	8.7594894	9.008793
Record Total Time	16.2	10.398	20.982

Table 13. Times When Local Sensor Aided by DARBC

Local Sensor Only	Average (sec)	Minimum Value (sec)	Maximum Value (sec)
Record Time to Detect	1.5131976	1.006176	1.9865094
Record Total Time	10.884	8.256	13.488

Table 14. Times for Unaided Local Sensor

Table 13 indicates that DARBC system on average takes 1.46 seconds to detect a high velocity target in the range between 500 km to 2000 km. Total time from first detection by DARBC to interceptor launch is 16.2 seconds.

Table 14 indicates that local sensor without aid of the DARBC radar takes an average of 1.51 seconds to detect high velocity target in the range between 50 km to 300 km. Total time from first detection to interceptor launch is 10.88 seconds. The comparison indicates that with the aid of DARBC radar the average local system engagement time improves from 10.88 seconds to 9.09 seconds.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The analysis concludes that implementation of the DARBC would fill a vital gap as a mobile, extended range sensor as part of the BMD program, providing the capabilities needed to defend our country and its allies from the Ballistic Missile threat as no other system can. If it is shown in future research that the Aperstructure concept can be physically realized and implemented to meet the technical requirements identified in this project, then the DARBC can be a very real asset to the USN and DoD.

B. RECOMMENDATIONS

This research project concluded that the OA concept as defined by the DARBC operational and technical requirements has the potential of providing a very real and significant benefit to the USN and BMD program. More analysis and research is recommended in a number of areas. Some of these may be good candidates for future COHORTs or NPS graduate students to pursue. Recommendations are provided in four primary topics; DARBC modeling, DARBC ship integration, DARBC operational requirements, and DARBC Life Cycle Cost.

1. DARBC Modeling

Future modeling efforts could be improved by combining the features of the individual modeling efforts used during this project and expanding for features not assessed. The expanded model would incorporate the benefits of the both system performance models such as stochastic processing along with more realistic representation of radar parameters and target characteristics. The model should have the following features:

- Threat representative 6 Degree Of Freedom (6 DOF) threat flight profile for various ballistic missiles. Targets would vary stochastically in flight path, target speed, and flight profile relative to the radar position.
- Earth's curvature & rotation considerations.

- Target RCS considering more realistic Swerling Case results, varying aspect angles, and influences of rocket motor plume enhancements during boost phase.
- Radar propagation analysis including environmental factors such as ducting, rain, fog and various operational conditions such as chaff. (This may be a special case model applicable to ASCM scenarios as opposed to BMD.)
- Stealth target RCS analysis to determine the effectiveness of the DARBC in the counter-stealth role.
- Weapon system engagement capabilities including complete detection, control and engagement sequence. An ability to select weapon capabilities and employment consideration (e.g. shoot-look-shoot vs. shoot-shoot-look) should be included. A variety of weapons including SM-3, marineized THAAD, marineized KEI weapon, and HEL, should all be included as engagement options.

The STK® family of modeling products generated by Analytical Graphics Inc. (AGI) was identified by the team as a viable COTS analysis tool that would provide some of the functionality described above. This tool should be a starting point for future modeling efforts by NPS or other activities investigating DARBC potential capabilities.

2. DARBC Ship Integration

This report touched lightly on a number of very critical technical risk areas impacting the eventual success of the DARBC concept. While work has been accomplished in aperstructures for superstructures, array T/R element integration into ship hull features remains critical to the success of a large scale array. A study solely focused on ship hull integration of T/R elements should be considered. This study could investigate hull strength impacts, antenna element features for transmissibility in a hull form, and anticipated ship flexure results. The study could also examine how element alignment and calibration would be accomplished during fabrication and then throughout the life cycle.

A study on ship flexure impacts and error budgets could examine and potentially calculate total error contributions across an entire system. This study would not necessarily need to be linked to DARBC as it could concentrate on developing compensation for dynamic flexure. This compensation concept could potentially support any sensors or systems impacted by ship flexure.

3. DARBC Operational Requirements

The DARBC system is currently a radar without a ship. The overall missions and weaponization of this platform need to be considered for the completion of DARBC operational capabilities definition. The Team was challenged to define radar capabilities when ship capabilities had to be assumed and availability of other potential sensors were unknown. Search pattern requirements is an area where sensor loading, capabilities of other ship sensors (on DARBC ship and integrated through ForceNet) and deployment environment need to be considered. The size and capability of DARBC could be considerably different if called to complete large scale fence search for ballistic missiles launch and volume search for stealth ASCMs simultaneously.

4. Life Cycle Cost Model

Supportability costs have the largest potential LCC impacts to DARBC. Ship integration of an opportunistic array has reliability and maintainability considerations that have never been considered to the scale of the DARBC system. Immediate access to radar components may be impossible to major sections of hull areas compared to today's "radar rooms". To address manning considerations, studies are required that will drive preventative maintenance to absolute minimal requirements. Corrective maintenance must not be critical to system performance. How to accomplish this affordably must be examined during early stages of DARBC development.

Strategies for future development and evaluation of DARBC should be investigated to bring concepts from paper study phase into systems that can be used to validate capabilities only shown by models. A SEP preparation could have been more beneficial to DARBC concept fruition than the ICD and CDD developed by this project.

Articulation of a path forward including identification of risk areas and possible options for mitigation is recommended. This SEP could help define additional study areas not recognized or considered by this team.

APPENDIX A. MATLAB RCS MODEL

Model RCS in VHF, UHF, and S-band Radar

```
function [rcs] = rcs_cylinder(r, h, freq, phi, CylinderType)
% rcs_cylinder_225MHz.m
% This program compute monostatic RCS for a finite length
% cylinder of circular cross-section.
% Plot of RCS versus aspect angle theta is generated at a specified
% input angle phi
% Last modified on August 27, 2006
 r = 2;          % radius of the circular cylinder
 h = 18;          % height of the circular cylinder
eps =0.00001;      % error in degree per specular
dtr = pi/180;      % one degree
freq = 225000000;  % frequency used
freqMH = num2str(freq*1.e-6); % frequency in MHz
lambda = 3.0e+8 /freq;      % wavelength
CylinderType= 'Circular';   % 'Circular'

CylinderType
'Circular'
   % Compute RCS from 0 to (90-.5)  degrees
   index = 0;
   for theta = 0.0:.1:90-.5
      index = index +1;
      thetar = theta * dtr;
      rcs(index) = (lambda * r * sin(thetar) / ...
         (8. * pi * (cos(thetar))^2)) + eps;
   end
   % Compute RCS for broadside specular at 90 degree
   thetar = pi/2;
```

```
    index = index +1;
    rcs(index) = (2. * pi * h^2 * r / lambda )+ eps;

    % Compute RCS from (90+.5) to 180 degrees
    for theta = 90+.5:.1:180.
        index = index + 1;
        thetar = theta * dtr;
        rcs(index) = ( lambda * r * sin(thetar) / ...
            (8. * pi * (cos(thetar))^2)) + eps;
    end
end

% Plot the results
figure(1)
delta= 180/(index-1);
angle = 0:delta:180;
plot(angle,10*log10(rcs),'k','linewidth',1.5);
grid;
xlabel ('Aspect angle, Theta [Degrees]');;
ylabel ('RCS - dBsm');
title  ([[CylinderType],'  Cylinder','  at Frequency = ',[freqMH],'  MHz']);


function [rcs] = rcs_cylinder(r, h, freq, phi, CylinderType)
% rcs_cylinder_425 MHz.m
% This program compute monostatic RCS for a finite length
% cylinder of circular cross-section.
% Plot of RCS versus aspect angle theta is generated at a specified
% input angle phi
% Last modified on August 27, 2006
 r = 2;          % radius of the circular cylinder
 h = 18;          % height of the circular cylinder
```

```
eps =0.00001;      % error in degree per specular
dtr = pi/180;      % one degree
freq = 425000000   % freqebcy in MHz
freqMH = num2str(freq*1.e-6); % frequency in MHz abbreviated
lambda = 3.0e+8 /freq;      % wavelength
CylinderType= 'Circular';   % 'Circular'

CylinderType
'Circular'
   % Compute RCS from 0 to (90-.5)  degrees
   index = 0;
   for theta = 0.0:.1:90-.5
      index = index +1;
      thetar = theta * dtr;
      rcs(index) = (lambda * r * sin(thetar) / ...
         (8. * pi * (cos(thetar))^2)) + eps;
   end
   % Compute RCS for broadside specular at 90 degree
   thetar = pi/2;
   index = index +1;
   rcs(index) = (2. * pi * h^2 * r / lambda )+ eps;
   % Compute RCS from (90+.5) to 180 degrees
   for theta = 90+.5:.1:180.
      index = index + 1;
      thetar = theta * dtr;
      rcs(index) = ( lambda * r * sin(thetar) / ...
         (8. * pi * (cos(thetar))^2)) + eps;
   end
end
% Plot the results
delta= 180/(index-1);
angle = 0:delta:180;
```

```
plot(angle,10*log10(rcs),'k','linewidth',1.5);
grid;
xlabel ('Aspect angle, Theta [Degrees]');;
ylabel ('RCS - dBsm');
title  ([[CylinderType],'  Cylinder','  at Frequency = ',[freqMH],'  MHz']);


function [rcs] = rcs_cylinder(r, h, freq, phi, CylinderType)
% rcs_cylinder_3300MHz.m
% This program compute monstatic RCS for a finite length
% cylinder of circular cross-section.
% Plot of RCS versus aspect angle theta is generated at a specified
% input angle phi
% Last modified on August 27, 2006
r = 2;           % radius of the circular cylinder
h = 18;           % height of the circular cylinder
eps =0.00001;     % error in degree per specular
dtr = pi/180;     % one degree
freq = 3300000000 % frequency in MHz
freqMH = num2str(freq*1.e-6); % abbreviate the Frequency
lambda = 3.0e+8 /freq;      % wavelength
CylinderType= 'Circular';   % 'Circular'

CylinderType
'Circular'
   % Compute RCS from 0 to (90-.5)  degrees
   index = 0;
   for theta = 0.0:.1:90-.5
      index = index +1;
      thetar = theta * dtr;
      rcs(index) = (lambda * r * sin(thetar) / ...
         (8. * pi * (cos(thetar))^2)) + eps;
```

```
    end
    % Compute RCS for broadside specular at 90 degree
    thetar = pi/2;
    index = index +1;
    rcs(index) = (2. * pi * h^2 * r / lambda )+ eps;
    % Compute RCS from (90+.5) to 180 degrees
    for theta = 90+.5:.1:180.
        index = index + 1;
        thetar = theta * dtr;
        rcs(index) = ( lambda * r * sin(thetar) / ...
            (8. * pi * (cos(thetar))^2)) + eps;
    end
end

% Plot the results
delta= 180/(index-1);
angle = 0:delta:180;
plot(angle,10*log10(rcs),'k','linewidth',1.5);
grid;
xlabel ('Aspect angle, Theta [Degrees]');;
ylabel ('RCS - dBsm');
title  ([[CylinderType],'  Cylinder','  at Frequency = ',[freqMH],'  MHz']);
```

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APPENDIX B. MAPLE RADAR TECHNICAL PARAMETERS MODEL

<u>DARBC_Radar_Parameters_Final.mws</u>

C:\Documents and Settings\Paul\Desktop

```
> #Naval Postgraduate School (NPS)
> #Masters of Science in Systems Engineering (MSSE)
> #Naval Surface Warfare Center (NSWC) Port Hueneme Division (PHD)
> #Team "R" Capstone Project, Radar Technical Parameters Research
> #23 August, 2006, PRD
>
> restart;  #Reset of Maple's Memory
> #Defining Radar Equation Parameters (see table in technote for definitions)
> P:=500000;p:=3E6;H1:=100;H1V:=146;H1U:=77;H2:=10;H3:=1;H4:=0.1;N:=1;E:=1;K:=1.38065E-23;T:=290;B1:=23000;B2:=44000;B3:=4E6;F:=10^(3/5);fa:=0.01;f1:=216E6;f2:=420E6;f3:=3E9;L1:=100;L2:=5;W1:=40;W2:=5;Ef:=0.7;n:=3411;
```

$$P := 500000$$

$$p := .3\ 10^{7}$$

$$H1 := 100$$

$$H1V := 146$$

$$H1U := 77$$

$$H2 := 10$$

$$H3 := 1$$

$$H4 := .1$$

$$N := 1$$

$$E := 1$$

$$K := .138065\ 10^{-22}$$

$$T := 290$$

$$B1 := 23000$$

$$B2 := 44000$$

$$B3 := .4\ 10^{7}$$

$$F := 10^{(3/5)}$$

$$fa := .01$$

$$f1 := .216\ 10^{9}$$

$$f2 := .420\ 10^{9}$$

$$f3 := .3\ 10^{10}$$

$$L1 := 100$$

$$L2 := 5$$

$$\mathrm{W1} := 40$$

$$\mathrm{W2} := 5$$

$$Ef := .7$$

$$n := 3411$$

```
> WL1:=299792458/f1;
```

$$WL1 := 1.387928046$$

```
> WL2:=299792458/f2;
```

$$WL2 := .7137915667$$

```
> WL3:=299792458/f3;
```

$$WL3 := .09993081932$$

```
> A1:=Ef*(n/2);
```

$$A1 := 1193.850000$$

```
> A2:=Ef*(n/2);
```

$$A2 := 1193.850000$$

```
> A3:=Ef*L2*W2;
```

$$A3 := 17.5$$

```
> G1:=(A1*4*Pi)/(WL1^2):
> G1db:=evalf(10*log10(G1),5);
```

$$G1db := 38.914$$

```
> G2:=(A2*4*Pi)/(WL2^2):
> G2db:=evalf(10*log10(G2),5);
```

$$G2db := 44.689$$

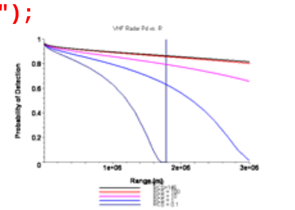
```
> G3:=(A3*4*Pi)/(WL3^2):
> G3db:=evalf(10*log10(G3),5);
```

$$G3db := 43.428$$

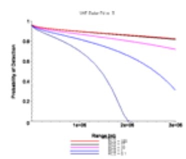
```
> RE1VHF:=(R1)^4=(P*G1*A1*H1V*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 146m^2
> RE1:=(R1)^4=(P*G1*A1*H1*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 100m^2
> REA1:=(R1)^4=(P*G1*A1*H2*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 10m^2
> REB1:=(R1)^4=(P*G1*A1*H3*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 1m^2
> REC1:=(R1)^4=(P*G1*A1*H4*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 0.1m^2
>
> RE1U:=(R2)^4=(P*G2*A2*H1*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 100m^2
> RE1UHF:=(R2)^4=(P*G2*A2*H1U*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 77m^2
> REA1U:=(R2)^4=(P*G2*A2*H2*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 10m^2
> REB1U:=(R2)^4=(P*G2*A2*H3*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 1m^2
> REC1U:=(R2)^4=(P*G2*A2*H4*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 0.1m^2
>
```

```
> RE1S:=(R3)^4=(p*G3*A3*H1*N*E)/(((4*Pi)^2)*K*T*B3*S3):# S-Band Radar Equation using RCS
of 100m^2
> REA1S:=(R3)^4=(p*G3*A3*H2*N*E)/(((4*Pi)^2)*K*T*B3*F*S3):# S-Band Radar Equation using
RCS of 10m^2
> REB1S:=(R3)^4=(p*G3*A3*H3*N*E)/(((4*Pi)^2)*K*T*B3*F*S3):# S-Band Radar Equation using
RCS of 1m^2
> REC1S:=(R3)^4=(p*G3*A3*H4*N*E)/(((4*Pi)^2)*K*T*B3*F*S3):# S-Band Radar Equation using
RCS of 0.1m^2
>
>
> P2VHF:=solve(RE1VHF,S1):
> P3VHF:=10*log10(P2VHF):
> RE2VHF:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=P3VHF:
> P4VHF:=solve(RE2VHF,D1):
>
> #P1:=eval(RE1):
> P2:=solve(RE1,S1):
> P3:=10*log10(P2):
> RE2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=P3:
> P4:=solve(RE2,D1):
>
> #PA1:=eval(REA1):
> PA2:=solve(REA1,S1):
> PA3:=10*log10(PA2):
> REA2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=PA3:
> PA4:=solve(REA2,D1):
>
> #PB1:=eval(REB1):
> PB2:=solve(REB1,S1):
> PB3:=10*log10(PB2):
> REB2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=PB3:
> PB4:=solve(REB2,D1):
>
> #PC1:=eval(REC1):
> PC2:=solve(REC1,S1):
> PC3:=10*log10(PC2):
> REC2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=PC3:
> PC4:=solve(REC2,D1):
>
> #P1U:=eval(RE1U):
> P2U:=solve(RE1U,S2):
> P3U:=10*log10(P2U):
> RE2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=P3U:
> P4U:=solve(RE2U,D2):
>
>
> P2UHF:=solve(RE1UHF,S2):
> P3UHF:=10*log10(P2UHF):
> RE2UHF:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=P3UHF:
> P4UHF:=solve(RE2UHF,D2):
>
> #PA1U:=eval(REA1U):
> PA2U:=solve(REA1U,S2):
> PA3U:=10*log10(PA2U):
> REA2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=PA3U:
> PA4U:=solve(REA2U,D2):
>
> #PB1U:=eval(REB1U):
> PB2U:=solve(REB1U,S2):
> PB3U:=10*log10(PB2U):
> REB2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=PB3U:
> PB4U:=solve(REB2U,D2):
>
> #PC1U:=eval(REC1U):
> PC2U:=solve(REC1U,S2):
```

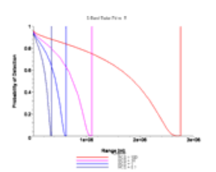
```
> PC3U:=10*log10(PC2U):
> REC2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=PC3U:
> PC4U:=solve(REC2U,D2):
>
> #P1S:=eval(RE1S):
> P2S:=solve(RE1S,S3):
> P3S:=10*log10(P2S):
> RE2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=P3S:
> P4S:=solve(RE2S,D3):
>
> #PA1S:=eval(REA1S):
> PA2S:=solve(REA1S,S3):
> PA3S:=10*log10(PA2S):
> REA2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=PA3S:
> PA4S:=solve(REA2S,D3):
>
> #PB1S:=eval(REB1S):
> PB2S:=solve(REB1S,S3):
> PB3S:=10*log10(PB2S):
> REB2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=PB3S:
> PB4S:=solve(REB2S,D3):
>
> #PC1S:=eval(REC1S):
> PC2S:=solve(REC1S,S3):
> PC3S:=10*log10(PC2S):
> REC2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=PC3S:
> PC4S:=solve(REC2S,D3):
>
> plot([P4VHF,P4,PA4,PB4,PC4],R1=0..8000000,D1=0..1,xtickmarks=3,labels=["Range
(m)","Probability of
Detection"],labeldirections=[HORIZONTAL,VERTICAL],legend=["RCS=146","RCS = 100","RCS =
10","RCS = 1","RCS =
0.1"],view=[0..3E6,0..1],color=[black,red,magenta,blue,navy],thickness=2,font=[HELVETICA,
BOLD,12],title="VHF Radar Pd vs. R");
```



```
> plot([P4U,P4UHF,PA4U,PB4U,PC4U],R2=0..8000000,D2=0..1,xtickmarks=3,labels=["Range
(m)","Probability of Detection"],labeldirections=[HORIZONTAL,VERTICAL],legend=["RCS =
100","RCS = 77","RCS = 10","RCS = 1","RCS =
0.1"],view=[0..3E6,0..1],color=[red,black,magenta,blue,navy],thickness=2,font=[HELVETICA,
BOLD,12],title="UHF Radar Pd vs. R");
```



```
> plot([P4S,PA4S,PB4S,PC4S],R3=0..8000000,D3=0..1,xtickmarks=3,labels=["Range
(m)","Probability of Detection"],labeldirections=[HORIZONTAL,VERTICAL],legend=["RCS =
100","RCS = 10","RCS = 1","RCS =
0.1"],view=[0..3E6,0..1],color=[red,magenta,blue,navy],thickness=2,font=[HELVETICA,BOLD,1
2],title="S-Band Radar Pd vs. R");
>
```



```
> eval(PB4S,R3=425000);#S-Band Radar's "Range" using 1m^2 RCS. (Range is R (450km))
(Result should be 0.5)
```

$$.4904985725$$

```
> eval(PA4S,R3=748000);#S-Band Radar's max Range for Handoff (Handoff Range is R (748km))
(Result should be 0.5)
```

$$.5000286862$$

```
> VHFPsubD:=evalf(eval(P4VHF,R1=748000),5);#VHF Pd at handoff range vs. Ballistic Missile
(146m^2 RCS)
```

$$VHFPsubD := .90616$$

```
> UHFPsubD:=evalf(eval(P4UHF,R2=748000),5);#UHF Pd at handoff range vs. Ballistic Missile
(77m^2 RCS)
```

$$UHFPsubD := .90651$$

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APPENDIX C. SUPPORTING DOCUMENTATION

The following documents were generated during the course of the research project. These documents and engineering notes supported the production of the Joint Applied Project (JAP) paper and are being listed in this appendix for reference use only. These documents were used internally by "Team R" to document and record the progress of the different studies and satisfy the requirements of the course. Differences between content in these attachments and the content in the body of the JAP paper reflect evolution of the project and should be disregarded. Information in the body of this paper is the latest information available from this study. References in this appendix were separated and are listed throughout this appendix and at the end of the document.

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INITIAL CAPABILITIES DOCUMENT
FOR
Digital Array Radar for BMD and Counter-Stealth
(DARBC)

Potential ACAT: **XXX**

Validation Authority: **Missile Defense Agency**

Approval Authority: **Missile Defense Agency**

Milestone Decision Authority: **Missile Defense Agency**

Designation: **TBD**

Prepared for **Milestone Decision A**

Version 1.03

Date: 1 May 2006

CHANGE HISTORY

The table below identifies all changes incorporated into the updated version of this document after initial approval. A change in twenty percent (20%) of the document constitutes a new version, which will also be identified in this table. The Change Request Number (CR #) provides a link to the history of the change request.

CR #	Date	Version #	Change Description
1	1 May	1.04	Initial draft for delivery to NPS

INTRODUCTION

United States Navy (USN) sources indicate a need for long range (order of thousands of kilometers) shipboard radar for Ballistic Missile Defense (BMD) to augment and expand current capabilities to defend against the increasing ballistic missile threat. The Naval Postgraduate School (NPS) is conducting radar architecture research based on an Opportunistic Array (OA) and is assessing the needed critical technologies to be incorporated into a ship-wide digital phased array radar.

The Digital Array Radar for BMD and Counter-Stealth (DARBC) radar will be a ship based sensor to provide long range search, detection and track of ballistic missiles. The increased in maximum detection range over existing shipboard sensors would provide a mobile early warning capability that can improve engagability by extending the time available for engagement decision making and providing improved track information for designation to other engagement sensors. This long range search capability would decrease the workload of existing BMD capable Aegis platforms so that those systems can focus on the closer range Air Defense (AD) mission.

The radar will have sufficient power, aperture and system characteristics necessary to perform the mission described and will be operating over the Very High Frequency (VHF) and Ultra High Frequency (UHF) frequency bands (216-225 MHz and 420-450 MHz respectively). A benefit of operating in the anticipated frequency ranges is enhanced counter-stealth AD capability.

The radar platform may be equipped with weapons of sufficient range and capability to provide boost, mid-course, and terminal phase engagements of Short Range Ballistic Missiles (SRBMs), Medium Range Ballistic Missiles (MRBMs), Intermediate Range Ballistic Missiles (IRBMs), Submarine Launched Ballistic Missiles (SLBMs), and Intercontinental Ballistic Missiles (ICBMs). The radar will provide large area surveillance necessary to detect the launch of ballistic missiles, both land and sea based, and track the missiles. The radar data will then be used to cue other sensors for purpose of engagement with defensive systems. The other sensors may be from the same ship or as part of the overall BMD architecture. The early detection, track and cueing will improve engagement by other BMD systems that currently are only capable of engaging the threat in midcourse or terminal phases of flight.

JOINT FUNCTIONAL AREAS AND CONCEPTS

The development of the DARBC system will apply BMD capabilities-based planning across the range of defined military operational requirements that pertains to the Universal Joint Task List (UJTL) CJCSM 3500.04D dated August 1, 2005, in order to meet mission requirements to defend the United States, its deployed forces and allies from ballistic missile threats. The DARBC system is being designed to counter a full spectrum of ballistic missile threats. The U.S. military leaders will be able to use the DARBC system to effectively apply a missile shield for an area defense ballistic missile threat. Should stealth air threats be present in the scanning area, the DARBC system will also be capable of detecting and tracking those threats.

RANGE OF MILITARY OPERATIONS

The concept of a forward deployed BMD force enables the USN to provide battlespace awareness enhancing the joint relationship between the U.S. military services which enhances the defense of our homeland as well as deployed U.S. and allied forces. By operating in a forward deployed region, ballistic missile launches can be detected earlier even when tracked above an adversary's homeland. A BMD umbrella can be formed for expeditionary land and sea forces as they move into the theater. The fight can be taken to the enemy's shores for asymmetric threats, such as theater ballistic missiles armed with nuclear, biological, or chemical warheads. The BMD concept assures enduring and emerging allied troops they are protected.

Battle management Command and Control (C2) covering forward deployed military operations can use the DARBC for independent search and detection, and tracking of ballistic missile launches in the early stages of flight. The current BMD concept that is only capable of supporting military operations against ballistic missile threats in midcourse and terminal flight phases. Also, the BMD concept can support military operations or homeland defense against ballistic missile threats launched from a surface ship or submarine threat. The BMD concept with the DARBC system can also support military operations covering counter stealth search, detection and tracking of airborne threats.

TIMEFRAME UNDER CONSIDERATION

The technology required to integrate the DARBC system into a new and advanced ship design will require several years of Research and Development (R&D) prior to achieving Initial Operational Capability (IOC) of the system. IOC is likely to depend largely on integration of the DARBC into either an existing development spiral of a ship construction program or into a new ship construction program. IOC for DARBC is projected for fiscal year 2019 or beyond.

REQUIRED CAPABILITY

OVERVIEW

This section will discuss the requirements needed for DARBC to meet the BMD, counter stealth, and other mission goals. The primary function of DARBC is shipboard exo-atmospheric surveillance, and tracking and preliminary discrimination of ballistic missiles. DARBC can be deployed on surface combatants or auxiliary class ships. The possible secondary uses of the DARBC include communications and electronic attack.

The radar architecture will utilize wireless networked Opportunistic Array (OA) and aperstructure concepts. The OA concept can be described as locating array elements at available open areas over the entire ship and integrated into the ship's superstructure and hull form above the waterline. The array is integrated throughout the ship and utilizes transmit-receive (T/R) modules. The T/R modules are self-standing with no hard wire connections, except for primary power, and also utilize wireless networking.

The DARBC architecture allows for flexibility and growth while incorporating redundancy for hardware errors. Hardware and software shall be easily incorporated. The radar

will be reconfigurable with selectable weights and elements used in beam forming for beam pattern control. Table 0-1 provides Battlespace Awareness goals that will be supported by the DARBC as a sensor element.

Table 0-1. Battlespace Awareness (BA) JFC Goals

Battlespace Awareness (BA) JFC Goals
Superior Information Position (Fight First for Information Superiority) – generate and exploit high quality shared awareness through better timeliness, accuracy and relevance of information. • Assure our own information access through a well-networked and interoperable force.
High Quality Shared Awareness – move to a capability to translate information and knowledge routinely into the requisite level of common understanding and situational awareness across the spectrum of participants. • Requires a collaborative network of networks, populated and refreshed with quality intelligence and non-intelligence data, both raw and processed to enable forces to build a shared awareness relevant to their needs. • Requires information users to become information suppliers, responsible for posting information before use.
Dynamic Self-Coordination – increase freedom of low-level forces to operate near autonomously and re-task themselves through exploitation of shared awareness and commander's intent. • Produce a meaningful increase in operational tempo and responsiveness. • Rapidly adapt when important developments occur in the battlespace and eliminate the step function character of military operations.
Dispersed Forces – move combat power from a fixed or constant position to noncontiguous operations. • Retain control of the battlespace and generate effective combat power at the proper time and place. • Increase close coupling of intelligence, operations and logistics to achieve precise effects and gain temporal advantage with dispersed forces.
Deep Sensor Reach • Leverage increasingly persistent Intelligence, Surveillance, Reconnaissance (ISR) to use sensors as a maneuver element as well as a deterrent when used as an overt display of intent or defensive reach capability.

Battlespace Awareness (BA) JFC Goals
Rapid Speed of Command – reduce the time required to recognize and understand a situation, and through battlefield innovation and adaptation compress sensor-to decision maker-to-shooter timelines to turn information advantage into decision superiority and decisive effects. This should include locking out an adversary's options and achieving option dominance.
Alter Initial Conditions at Increased Rates of Change – exploit the principles of high quality shared awareness, dynamic self-coordination, dispersed and de-massed forces, deep sensor reach, compressed operations and levels of war, and rapid speed of command to enable the joint force, across the cognitive, information and physical domains of warfare, to swiftly identify, adapt to and change an opponent's operating context to our advantage.

LOGISTICS SUPPORT CONCEPT

The DARBC system will employ a maintenance support concept based on minimal manning and a high usage rates. The system will have minimum maintenance requirements, utilizing distance support, automation, and fault tolerance to provide a highly available system capable of supporting a high demand mission profile.

JOINT FORCE CAPABILITIES (JFC)

The joint force capabilities of the DARBC are listed in Table 0-2.

Table 0-2. JFC Capabilities

JFC Capabilities
DARBC will provide search functions and set up based on sensor or intelligence source and data latency. User defined search capability will also exist. Search types will include cued from ship organic sensor, cued from BMD sensor in Joint Battle Management Command and Control (JBMC2) architecture, horizon, and fence.
DARBC will provide sensor data to the Global Information Grid (GIG) to extend the level of data interoperability; expand collaborative communications connectivity; shared awareness; and integration and acceleration of kill chain execution with other sensors against ballistic threats.
DARBC will provide long range tracking of ballistic missile threats through ascent and mid-course phases of flight. Track can be maintained while DARBC continues to provide search.
DARBC will provide all weather performance. The system will operate in sea state 5.
DARBC will provide Line of Sight (LOS) and satellite UHF communication.

JFC Capabilities
Provide situational awareness to joint forces and civilian population about imminent threats from incoming ballistic missile or stealth targets.
DARBC will calculate predicted launch origin and time and impact location and time for any ballistic missiles tracked.
DARBC will require limited onboard maintenance. Availability of the system will be above 95% under a heavy duty cycle and mission profile.

CONCEPT OF OPERATIONS SUMMARY

The DARBC radar will provide long range search, detection and track of the various types of ballistic missiles for cueing to other organic sensors or sensors and systems in the overall Joint Battle Management Command and Control (JBMC2) network. The radar will provide early detection of ballistic missile launches over large areas of land or sea space not currently or adequately covered by existing sensors. The ship configured with DARBC will be forward deployed to a position where it has greatest potential for detection of launches. Early detection and tracking increases overall engagement timeline, providing more time for decision making, weapon assignment, and weapon engagement from the overall BMD family of systems. Early detection using forward based sensors permits engagement of ballistic missile threats during boost and ascent phase when the threats are slower, larger and easier to engage.[xlvii] The early detection, track and cueing will improve engagement by other BMD systems that engage the threat in midcourse or terminal phases of flight. Deployment of the ship to provide midcourse and terminal search, detection, and tracking of ballistic missiles is possible as well. Secondary threats that the radar will support search, detection and track of are stealth air threats. Detection of these threats will be at ranges where they pose a direct threat to the ship or units in the immediate operation area either by launch of weapons or as weapons themselves. The radar also provides capabilities to support UHF communications either in line of sight or by SATCOM link.

BALLISTIC MISSILE DEFENSE MISSION

BMD is best accomplished using a layered defense/combined arms approach. There are too many threats in existence to rely on hard kill defenses only requiring need to attrite enemy capability using Information Operations (IO) / Electronic Attack (EA) / Strike. Depth of fire with SM-3 is limited – generally one, max of two.[xlviii] Detection of Ballistic missiles can be enhanced from prior knowledge of launch location, time and target type. When intelligence can provide some of this information, especially location, specific search patterns can be generated to increase probability of detection. Space based assets can monitor large areas and cue sensors when launches have been detected. As a forward deployed combatant, the ship will potentially be exposed to direct attack by the state posing the ballistic missile threat. The ship and radar will need to be able to counter threats of anti-ship cruise missiles through soft and hard kill methods. The radar design should enhance signature reduction of radar cross section (RCS) and Infra Red

(IR). The ship/radar will need to be available on station for long periods of time regardless of weather and sea conditions. When ship is positioned to defend a terminal position, the radar must be capable of detecting the threat at ranges suitable for terminal engagements. These threats include re-entry vehicle (RV) as well as the associated debris and decoys of the threat.

CAPABILITY GAP

Search and detection of ballistic missiles is a difficult task exacerbated by the large quantities of ballistic missiles available in the world today, by their increased capabilities of range, speed, and reduced signatures, and by the increased flexibility to launch these weapons from submarines, and asymmetric platforms such as surface ships. Current Navy systems lack the quantity and range to provide sufficient coverage.[xlix] Current platforms must manage their radar resources across BMD search and detection as well as general AD coverage missions. Upgrades and additional deployment of sensors such as Cobra Dane and Sea based terminal do not provide sufficient early warning and track history of launches do to their limited quantity and fixed locations. Forward presence by Aegis Cruisers and Destroyers provide some search capability but these platforms are limited in range and share the same sensor for AD and BMD search. Future missile and high energy weapons such as the Kinetic Energy Interceptor (KEI) and High Energy Laser (HEL) will provide greater capability for engagements in boost and ascent phase, increasing need for long range sensor to support their capabilities.[l] Destroying a ballistic missile during boost or ascent phase would dramatically increase the defended area and has the advantage that the weapon will fall back into shooter's territory, eliminating the need and concerns of destroying the warhead. Current ship based sensors lack range capability for detection and track to support future ship based KEI missiles. Potential for sea based launches of ballistic missiles increases need for ocean based surveillance. Long range surveillance capability reduces quantity of assets required to cover sea based launches. Aegis capability is currently limited to short and medium range ballistic missiles during their midcourse flight. SRBMs with depressed trajectories may also not allow engagement by exo-atmospheric systems such as SM-3.[li][lii]

The MDA's strategy is to evolve the current capability to improve defenses against all threats in all phases of flight with emphasis on longer range missiles and engagement during boost and ascent phase. To fill the gap, the strategy will feature greater sensor and interceptor mobility.[liii] The Sea Based Terminal X-band radar enters service in 2006 providing a sea-based mobile midcourse radar that can be based in the Pacific Ocean. This system will share test bed asset functions in addition to operational requirements and lacks mobility of speed to transit to optimum locations. While multiple Sea Based Terminals are possible they will lack the numbers and associated interceptors to provide worldwide mobility.

Table 0-1. Live Sample of Capability Gaps[liv]

Priority / Key Indicator	JOpsC Key characteristics	Description	Parameters	Minimum Value
		Search volume		
		Area coverage fence search	km^2	TBD
		Detection		
		Detection range	km	1500 km MAX
		Detection	km	100 km MIN
		Probability of detecting target launch, includes search time.	P of detection for nominal target size	
		Of enemy aircraft detected in time to allow second engagement.	percent	TBD
		Of enemy aircraft passing through coverage area detected.	percent	TBD
		Of targets lost after detection.	percent	TBD
		Beyond engagement range aircraft detected.	km	TBD
		From sensor enemy air raid detected.	km	TBD
		From sensor single enemy aircraft detected.	km	TBD
		Reaction Time		
		After launch of ballistic missile attack on US, attack assessment issued.	minutes	TBD
		After launch of ballistic missile attack on US forces, attack assessment issued to theater ballistic missile (TBM) forces.	minutes	TBD
		Of threat warnings to TBM forces are false.	percent	TBD
		After launch, geographic combatant commander provided assured warning of theater ballistic missile launch.	minutes	TBD
		For ballistic missile to be detected (after launch).	minutes	TBD
		Detect to Engage		

Priority / Key Indicator	JOpsC Key characteristics	Description	Parameters	Minimum Value
		Of attacking missiles successfully penetrated friendly defenses culminating in warhead delivery or function on target.	percent	TBD
		Of detected ballistic missile launches, provide cueing for counterforce operations.	percent	TBD
		Of launched ballistic missiles, destroyed before impact.	percent	TBD
		Of launched cruise missiles (of all types) destroyed before impact.	percent	TBD
		Of combatant commander specified areas of interest covered for ballistic missile warning.	percent	TBD
		Of commander's area has required reconnaissance and surveillance coverage.	percent	TBD
		Of enemy aircraft detected in time to allow weapons employment.	percent	TBD
		Of electronic attacks achieve desired effects on enemy.	percent	TBD

Table 4-2: Specific Capability Gaps

UJTL Functional Area	Joint Functional Concept	Capability Gaps
SN 3.4.2 Provide Integrated Tactical Warning and Attack Assessment	Joint Battle space awareness	Existing sensors lack forward presence and mobility to provide early warning. Existing sensors lack sufficient situational awareness to conduct attack operations against re-locatable, time critical (RTC) theater missile threats; e.g. , TELs.

UJTL Functional Area	Joint Functional Concept	Capability Gaps
SN 3.4.3 Coordinate Strategic Ballistic Missile Defense	Joint Global Deterrence	Existing sensors lack range and search capability to provide launch detection of threats for engagement during boost or ascent phase. Existing sensors lack ability to recognize and react to all theater air and missile threats.
ST 6.1 Provide Theater Aerospace and Missile Defense	Joint Air Operations	Existing sensors lack capability (operating independently or as part of a Joint/Combined Force) to detect and maintain a single and continuous track on each air and space vehicle within the assigned battlespace.
ST 6.1.6 Support Tactical Warning and Attack Assessment in Theater	Joint Air Operations	Existing sensors lack forward presence and mobility to provide early warning. Existing sensors lack sufficient situational awareness to conduct attack operations against Sea based, re-locatable, time critical (RTC) theater missile threats; e.g. , Submarines, asymmetric attack by surface vessel
OP 6.1.5 Conduct Joint Operations Area Missile Defense (Includes Homeland Defense for this ICD)	Joint Air Operations Joint Homeland Defense	Existing sensors lack forward presence and mobility to provide early warning. Existing sensors lack sufficient situational awareness to conduct attack operations against re-locatable, time critical (RTC) theater missile threats; e.g. , TELs. Existing sensors lack capability (operating independently or as part of a Joint/Combined Force) to detect and maintain a single and continuous track on each air and space vehicle within the assigned battlespace.

THREAT/OPERATIONAL ENVIRONMENT

The Radar will be deployed in one of two basic scenarios. The first is to be forward deployed near a projected threat country or area positioned to search for ballistic missile launches. The second is a homeland defense position where the ship will be positioned to detect sea based launches from submarines or undisclosed threat surface ships. The forward deployed scenario could put the ship in a position where it is in harms way. Because the time line between detection and engagement is very short, shooters, armed with very fast interceptors or lasers, must be stationed close to the launch location. The sheer closeness of this position means that the shooters are subject to interception and attacks themselves. The ship will be subject to the same threats posed to current and future surface combatants such as Anti Ship Cruise Missiles (ASCMs) and other air, surface, and subsurface threats. The ship can be expected to be deployed and positioned for long periods of time while on station providing surveillance.

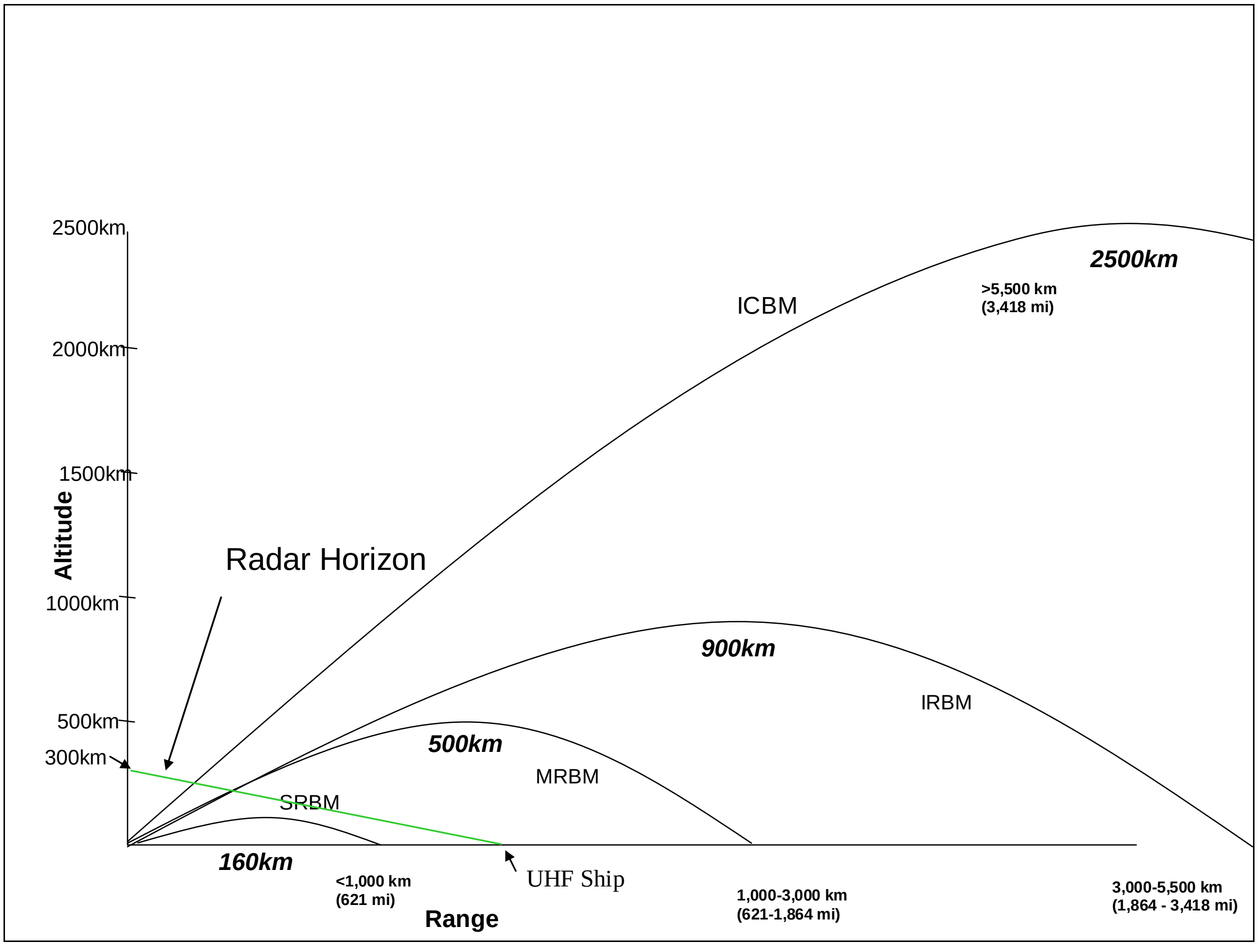
The ship/radar would normally be operated in conjunction with other BMD units. These units could be Patriot or Aegis platforms providing terminal phase defense. Where long range ballistic missiles are launched, BMD fixed assets in Alaska or CONUS will be cued to support mid course tracking in support of Ground Based interceptors or other engagement means.

Ballistic missiles have proliferated over the last four decades and are now prevalent across the globe with over 24 countries capable of launching some form of this threat. As an example, over 100 foreign ballistic missile launches occurred around the world in 2004.[lv] Many countries also have capability to configure these missiles with Weapons of Mass Destruction (WMDs) including nuclear, chemical and biological payloads. Additionally submarines can launch Ballistic Missiles dramatically increasing threat launch areas increasing surprise and need for sensors with increased capabilities and search volume. Ballistic Missiles are classified in the following 5 main categories as described by the following table.

Table 0-1. Ballistic Missile Flight Path Characteristics

Ballistic Missile Category	Maximum Range	Apogee
Short-range ballistic missile (SRBM)	<1,000 km (621 mi)	160 km
Medium-range ballistic missile (MRBM)	1,000-3,000 km (621-1,864 mi)	500 km
Intermediate-range ballistic missile (IRBM)	3,000-5,500 km (1,864 - 3,418 mi)	900 km
Intercontinental ballistic missile (ICBM)	>5,500 km (3,418 mi)	2500 km
Submarine-launched ballistic missile (SLBM)	Any ballistic missile launched from a submarine, regardless of maximum range	Varies

The range and apogees reported are examples of maximum capabilities. Trajectories can support shorter ranges with lower or depressed apogees. Some may fly a trajectory that has a lower apogee to achieve maximum range. A ballistic missile is a projectile that has been given some level of initial power, operates within the earth's atmosphere or the immediate space above the atmosphere, and follows a path governed mainly by the laws of gravity. Notional trajectories for the above categories are depicted in the following figure.



Ballistic Missile Flight Paths

FUNCTIONAL SOLUTION ANALYSIS SUMMARY

Non-materiel approaches which could enhance the military's detection of BMD threats would be to reorganize the deployment of Aegis platforms so that the AN/SPY-1 Radar Systems are forward deployed close enough to the anticipated threats to detect launches of ballistic missiles and/or to take a sea-based platform which hosts an existing BMD search radar and move it to a forward deployed position. These approaches would make use of our existing capabilities to enhance our picture of the battlefield. These approaches would require movement/adjustment of existing deployment schedules for battle groups.

One materiel approach necessary to address the capability gaps described includes developing the DARBC system to be implemented on new construction surface combatants. The DARBC system will be capable of mitigating the capability gaps described in Section 4 of this document. This system will be installed on future surface combatants. Additional platforms such as auxiliary class ships could provide additional flexibility and reliability through

redundancy. Another materiel approach would be to develop a similar system, which would be installed on existing surface combatants that would have the same capabilities as the DARBC. Back-fitting existing platforms with a system with ship integration needs of the DARBC would likely have significant impact to existing ship design. These combatants would also require a change in mission and deployment as their use in providing air defense for Carrier Strike Groups (CSGs) and Expeditionary Strike Groups (ESGs) would be modified in order for these platforms to be forward deployed.

The non-materiel approaches would provide a benefit of better detection of ballistic missiles but would require CSGs and ESGs be deployed with reduced AD coverage or require additional Aegis platforms to be procured. Whether Aegis ships or other sea-deployed radar platforms are used, escort services would be required to defend these assets which would have a large impact on the Navy's deployment schedule. Also, these non-materiel solutions would only address the BMD threats and would not address the capability gaps related to the Counter-Stealth mission. The non-materiel approaches would definitely be cheaper than the materiel ones so there is a tradeoff present between cost and capability.

In order to address all the current capability gaps listed in Section 4, a new system needs to be developed which meets requirements that mitigate the gaps in our current capability. Two materiel solutions exist which could meet these requirements. The differences between them are which platforms the systems will be installed on. The DARBC system will be a new system to be installed on future surface combatants, which are not yet developed. This provides both benefits and challenges. Benefits include have a "blank canvas" for development purposes which allows the design to not be hindered by existing physical features of current platforms.

One major feature of the DARBC system is the Aperstructure, which integrates the radar array with the hull of the ship. Development of this Aperstructure would benefit from the "blank canvas" of future surface combatants. Challenges for the DARBC include coming up with the new technology of integrating radar array elements into the hull of the ship. New technology will have to be developed for this to be implemented. Developing another system that would go on current surface combatants would be a benefit in that the platforms would be eventually modernizes with a new capability, extending their service life and possibly delaying the need to development of future combatants. The downside of this approach is that current platforms would have to be taken out of service for research, development, testing, and installation of this system. Also, integration of a new system into all the existing systems of current platforms would be more difficult than starting with a "blank canvas".

FINAL RECOMMENDATIONS

The recommended materiel solution is to develop new shipboard DARBC System on future ships to conduct the Ballistic Missile Defense mission. New DARBC system will mitigate the capability gaps addressed in section 4. This materiel approach is considered the most effective for improving long-range coverage, providing adequate target discrimination data for handover to another sensor or interceptor, and eliminating the requirements to conduct AD search. The following outlines the advantages of this materiel solution.

Improve long-range coverage: The radar provides autonomous search at ranges greater than 1,000 km. When a target is detected, a precision search function is used to discriminate booster from the warhead and transition to target tracking.

Adequate target discrimination data for handover: The radar provides adequate target track resolution precise enough to cue existing BMD sensors so they can detect and track the target.

Reduce the existing Aegis requirements to support ballistic missile search functions: DARBC will take over the responsibility for this requirement, permitting the Aegis system to concentrate on the AD mission and surface search. Aegis platforms can optimize location to support engagement rather than search requirements.

ANALYSIS OF ALTERNATIVES (AOA)

Each of the presented materiel solution approaches has its strengths and weaknesses. In Table 0-1, the materiel approaches that have been presented are discussed.

Table 0-1: Materiel Solution Analysis

APPROACH	PURPOSE	STRENGTHS	WEAKNESSES
Install DARBC system on existing ship platform	Early detection of threats	Long range detection and tracking capability, mobility	Cost, lack of existing ships for full area coverage, lost of escort capability
Install DARBC system on new class of ships tailored to address Ballistic Missile mission	Early detection of the threats	Long range detection and tracking capability, large field of view, and rapid response time	BMD mission capability, new technology, integration, and cost

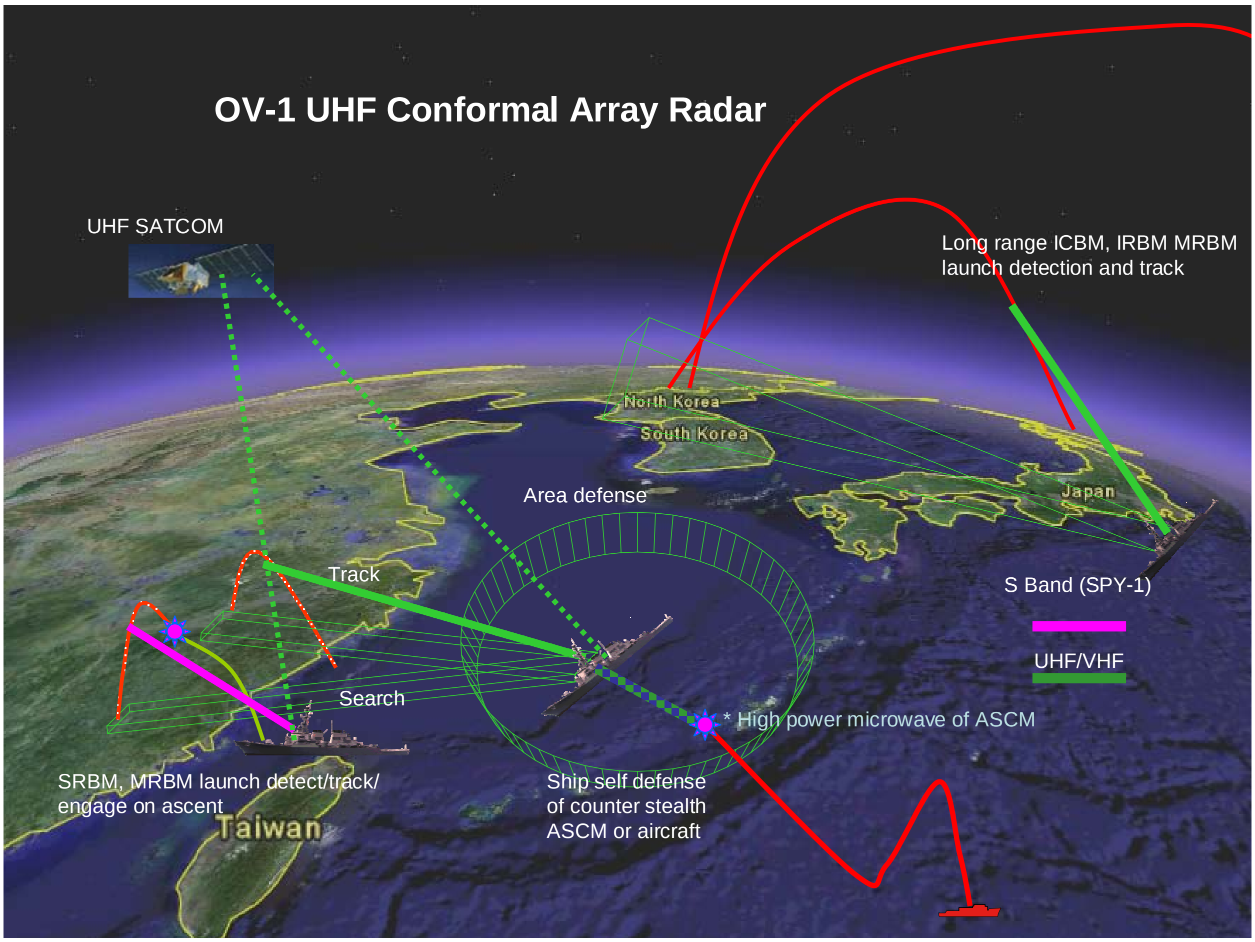
Appendix A: ACRONYMS

ACRONYM	DEFINITION
AD	Air Defense
AOA	Analysis of Alternatives
ASCM	Anti-Ship Cruise Missile
BA	Battlespace Awareness
BMD	Ballistic Missile Defense
C2	Command and Control
CJCSM	Chairman of the Joint Chiefs of Staff Manual
CONUS	Continental United States
CR #	Change Request Number
CSG	Carrier Strike Group
DARBC	Digital Array Radar for BMD and Counter-Stealth
DoD	Department of Defense
EA	Electronic Attack
EMCON	Emission Control
ESG	Expeditionary Strike Group
FP	Force Protection
HEL	High Energy Laser
ICBM	Inter-Continental Ballistic Missile
ICD	Initial Capabilities Document
IO	Information Operations
IOC	Initial Operational Capability
IR	Infra-Red
IRBM	Intermediate Range Ballistic Missile
ISR	Intelligence Surveillance Reconnaissance
JBMC2	Joint Battle Management Command and Control
JFC	Joint Functional Concept
KEI	Kinetic Energy Interceptor
LORA	Level of Repair Analysis
LOS	Line of Sight
MHz	Megahertz
MRBM	Medium Range Ballistic Missile
NCOW	Network-Centric Operations and Warfare
OA	Opportunistic Array
OV	Operational View
RADHAZ	Radiation Hazard
RCS	Radar Cross Section
RV	Re-entry Vehicle
SATCOM	Satellite Communication
SLBM	Submarine Launched Ballistic Missile
SM-3	Standard Missile - 3
SPY-1	AN/SPY-1 Radar
SRBM	Short Range Ballistic Missile
T/R	Transmit-Receive
TBD	To Be Determined
TBM	Theater Ballistic Missile

ACRONYM	DEFINITION
U.S.	United States
UHF	Ultra High Frequency
UJTL	Universal Joint Task List
USN	United States Navy
VHF	Very High Frequency
WMD	Weapons of Mass Destruction

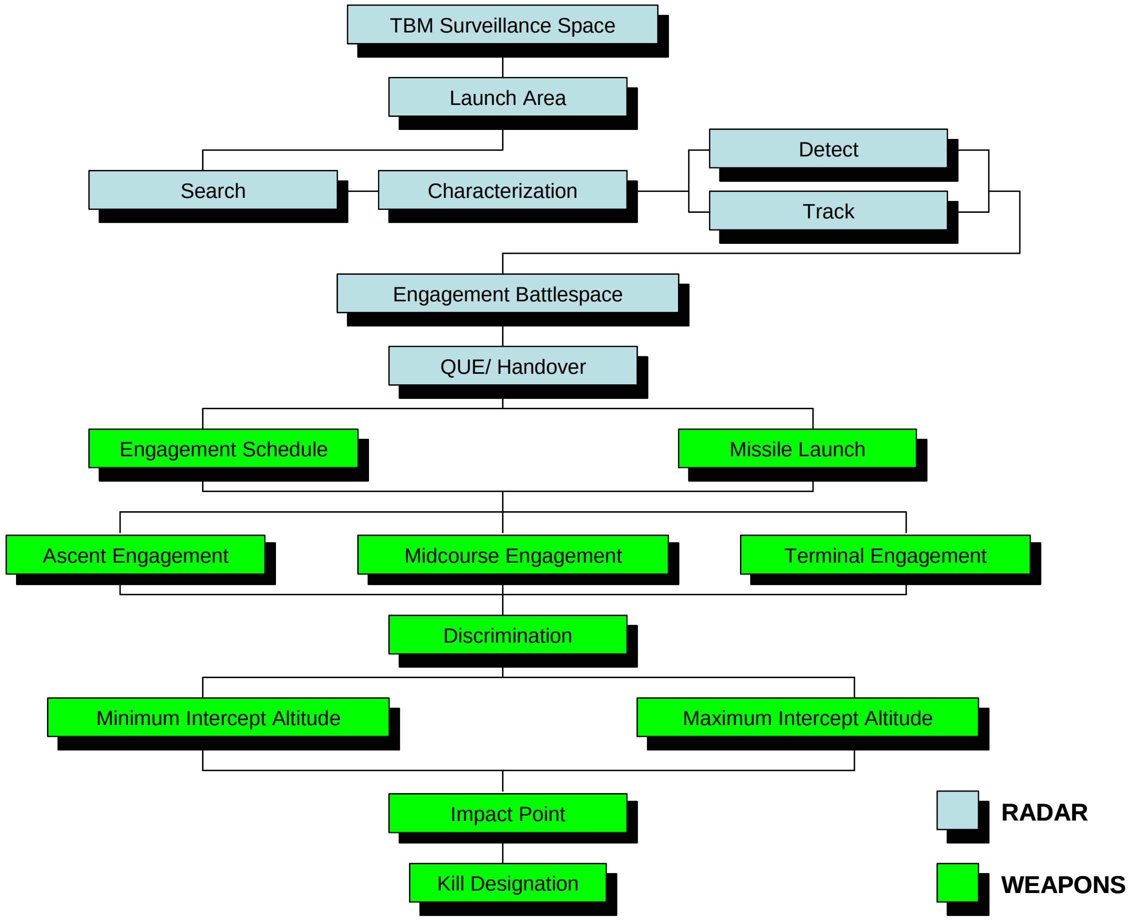
Appendix B: OV-1

OV-1 High-Level Operational Concept



Appendix C: OV-2

OV-2 Second Level Operational Processes



CAPABILITIES DEVELOPMENT DOCUMENT

FOR

Digital Array Radar for BMD and Counter-Stealth (DARBC)

Increment: **1**

ACAT: **II**

Validation Authority: **Missile Defense Agency**

Approval Authority: **Missile Defense Agency**

Milestone Decision Authority: **Missile Defense Agency**

Designation: **Independent**

Prepared for: **Milestone Decision B**

Version: 1.00

Date: 2006-09-01

EXECUTIVE SUMMARY

The purpose of this CDD is to define the operational attributes of the Digital Array Radar for Ballistic Missile Defense and Counter-Stealth (DARBC) radar necessary to design a proposed system.

United States Navy (USN) sources indicate a need for long-range (order of thousands of kilometers) shipboard radar for Ballistic Missile Defense (BMD) to augment and expand current capabilities to defend against the increasing ballistic missile threat. The Naval Postgraduate School (NPS) is conducting radar architecture research based on an Opportunistic Array (OA) and is assessing the needed critical technologies to be incorporated into a ship-wide digital phased array radar.

The DARBC radar will be a ship-based sensor to provide long-range search, detection and track of ballistic missiles. The increase in maximum detection range over existing ground-based and shipboard sensors would provide a mobile early warning capability that can improve engagement, by extending the time available for engagement decision making and providing earlier track information for designation to other engagement sensors. This increases opportunities to engage and re-engaging targets increasing overall probability of kill. This long-range search capability would decrease the workload of existing BMD capable Aegis platforms so that those systems can focus on the closer range Air Defense (AD) mission.

The radar platform, or other platforms receiving data from the DARBC, may be equipped with weapons of sufficient range and capability to provide boost, mid-course, and terminal phase engagements of Short Range Ballistic Missiles (SRBMs), Medium Range Ballistic Missiles (MRBMs), Intermediate Range Ballistic Missiles (IRBMs), Submarine Launched Ballistic Missiles (SLBMs), and Intercontinental Ballistic Missiles (ICBMs). The radar will provide large area surveillance necessary to detect the launch of ballistic missiles; both land and sea based, and track the missiles. The radar data will then be used to cue other sensors for the purpose of engagement with weapon systems. The other sensors may be from the same ship or as part of the overall BMD architecture. The early detection, track and cueing will improve engagement by other BMD systems that currently are only capable of engaging the threat in midcourse or terminal phases of flight.

This document summarizes the Concept of Operations (CONOPS) and describes the projected threat the Radar is intended to counter. Key Performance Parameters (KPPs) are defined and used to address the radar system capabilities and supportability requirements. This CDD also identifies key program risk areas that can impact cost and schedule.

This document was prepared by the Radar group of the Naval Postgraduate School, Master of Science System Engineering (MSSE) program. This CDD focuses only on the radar as a sensor despite potential functionality in shipboard communications due to the scope and time limits of the project. The CDD also excluded capabilities of the DARBC ship and associated weapon systems to support missions including BMD We concluded that it is necessary to develop the DARBC on future ships in order to conduct BMD missions.

CHANGE HISTORY

The table below identifies all changes incorporated into the updated version of this document after initial approval. A change in twenty percent (20%) of the document constitutes a new version, which will also be identified in this table. The Change Request Number (CR #) provides a link to the history of the change request.

CR #	Date	Version #	Change Description
1	3 August	1.0	Revision 1 of CDD
2	1 September	2.0	Revision 2 of CDD

CAPABILITY DISCUSSION

Search and detection of ballistic missiles is a difficult task exacerbated by the large quantities of ballistic missiles available in the world today, by their increased capabilities of range, speed, and reduced signatures, and by the increased flexibility to launch these weapons from submarines, and asymmetric platforms such as surface ships. Current Navy systems lack the quantity and range to provide sufficient coverage.[lvi] Current platforms must manage their radar resources across Ballistic Missile Defense (BMD) search and detection as well as general Air Defense (AD) coverage missions. Upgrades and additional deployment of sensors such as Cobra Dane and Sea based terminal do not provide sufficient early warning and track history of launches due to their limited quantity and fixed locations. Forward presence by Aegis Cruisers and Destroyers provide some search capability but these platforms are limited in range and share the same sensor for AD and BMD search.

Future missile and high-energy weapons such as the Kinetic Energy Interceptor (KEI) and High Energy Laser (HEL) will provide greater capability for engagements in boost and ascent phase, increasing need for long-range sensor to support their capabilities.[lvii] Destroying a ballistic missile during boost or ascent phase dramatically increases the defended area and has the advantage that the weapon will fall back into shooter's territory, eliminating the need to and concerns of destroying the warhead. Current ship based sensors lack the detection and track range capability to support future ship-based KEI systems. The potential for sea-based launches of ballistic missiles increases the need for sea-based surveillance. Long range surveillance capability reduces the quantity of assets required to cover sea-based launches. Aegis capabilities are currently limited to engagements during midcourse phases for short- and medium-range ballistic missiles. Short Range Ballistic Missiles (SRBMs) with depressed trajectories may not be able to be engaged by exo-atmospheric systems such as SM-3.[lviii,lix]

The Missile Defense Agency's (MDA's) strategy is to evolve the current capability to improve defenses against all threats in all phases of flight with emphasis on longer-range missiles and engagement during boost and ascent phase. To fill the gap, the strategy will feature greater sensor and interceptor mobility.[lx]

The Initial Capabilities Document (ICD) for the Digital Array Radar for BMD and Counter-stealth (DARBC) describes a ship-based sensor capable of providing long range search, detection and track of ballistic missiles. The increase in maximum detection range over existing shipboard sensors would provide a mobile early-warning capability that can improve engagement capability by extending the time available for engagement decision-making and providing improved track information for designation to other engagement sensors. This long-range search capability would decrease the workload of existing BMD capable Aegis radar systems so that those systems can focus on the closer range AD mission.

The DARBC will have sufficient power, aperture, and system characteristics necessary to perform the mission described and will be operating over the Very High Frequency (VHF) and Ultra High Frequency (UHF) frequency bands (216-225 MHz and 420-450 MHz respectively). A benefit of operating in the anticipated frequency ranges is enhanced counter-stealth AD capability. The DARCB will employ new aperstructure technology in which the radar array is integrated within the skin of the ship. The radar system will explore the Opportunistic Array

(OA) concept in which the Transmit/Receive (T/R) elements of the radar can be opportunistically place where space is available on the hull or superstructure of the host platform.

The development of the DARBC system will apply BMD capabilities-based planning across the range of defined military operational requirements that pertains to the Universal Joint Task List (UJTL) CJCSM 3500.04D dated August 1, 2005, in order to meet mission requirements to defend the United States, its deployed forces and allies from ballistic missile threats. The DARBC system is being designed to counter a full spectrum of ballistic missile threats. The U.S. military leaders will be able to use the DARBC system to effectively apply a missile shield for an area defense ballistic missile threat. Should stealth air threats be present in the scanning area, the DARBC system will also be capable of detecting and tracking those threats. [lxi] This current increment of the DARCB moves the USN closer to obtaining the operational capabilities required to adequately defend the US against the ballistic missile threat.

The DARBC will operate at sea onboard a future USN surface combatant due to the Research & Development (R&D) required to achieve the OA and Aperstructure concepts. The DARBC will meet standard USN requirements for radar systems operating in a sea environment. It will be forward deployed, designed to operate off the coasts of hostile countries that threaten the US with ballistic missiles. This forward deployed concept will increase the probability of an early detection of a ballistic missile launch, providing more time to make decisions and react to the threat.

The DARBC will be a stand-alone system with an external communications interface for passing target designation information. Data from the DARBC could then be passed to other combat systems, radar systems, and weapons systems via a joint communications system such as FORCEnet. These interfacing systems will be required to maximize the benefit of the DARBC. The development of the DARBC should coincide with the development or fielding of these interfacing systems. The DARBC will be able to provide situational awareness that no other system can provide to the joint US armed forces.

ANALYSIS SUMMARY

In order to adequately define both the need for and the requirements for the DARBC system, research was required in many areas. Initially an Analysis of Alternatives (AoA) was conducted between the capabilities presented by current USN systems that can support the BMD mission and a new set of systems made up of current technology, and new technology including the DARBC. The AoA showed that the DARBC was a system that could fill a void in the current capability to counter the ballistic missile threat and the results were documented in the ICD for the DARBC, May 2006.

In the quest to define the operational and technical requirements of the DARBC system, key research was conducted in the many areas. Whitepapers (technotes) were written detailing the research done on these topics and their results. Full versions of these technotes including results of the analysis will be included in a later revision of this document. A brief description of each of the research areas is described below.

CONCEPT OF OPERATIONS (CONOPS)

The CONOPS for the DARBC was written to detail the threats, associated capability gaps, and how the DARBC would operate. In this research, initial concepts for the system were discussed including the concept of the OA and the Aperstructure. The development of the 1st Operational View (OV-1) was a key point in the concept of the system. The modes of operation for the system were defined including searching, cueing (or being cued), and tracking. Anticipated operational capabilities were discussed as well as the operational scenarios for the system. The initial concepts of the system included using the VHF and UHF bands for their ability to detect targets at great ranges as well as their ability to detect stealth air threats.

THREAT RADAR CROSS SECTION (RCS)

The threat, defined in the CONOPS technotes, was analyzed and a RCS modeling tool was developed to generate the radar profile of the threat that could be seen by the DARBC including both the ballistic missile and stealth air threats.

ARRAY DENSITY REQUIREMENTS

Based on the frequencies in use and the OA concept, minimum distance spacing of the array elements on the exterior of the platform was calculated. This minimum spacing value was the closest distance that the array elements could be place together without causing interference to one another. This data was required by other related research in order to determine the overall size of the OA as well as to quantify the "Opportunistic" term with the OA concept.

RADAR PARAMETERS

The radar parameters research focused on the characteristics of the DARBC and their relationship to the operational requirements for the system. The requirements defined by the ICD for the DARBC, such as Probability of Detection (Pd) could only be achieved if the physical characteristics of the radar were calculated and defined properly. Parameters such as antenna gain, noise values, and power were calculated and modeled in order to determine a range of values for each parameter which if implemented would result in a radar system capable of meeting the operational requirements. Supporting data was taken from related theses and other studies done on the OA concept.

SEARCH PATTERN OPTIONS

Research was done to determine the best methods of employing the radar in a tactical scenario. Based on the capabilities of the radar, the optimal search patters were defined in an effort to minimize reaction time should a threat be present. Data from this research would drive the tactical program(s) for the DARCB and will have a large affect on the operational effectiveness of the system.

OBSERVE ORIENT DECIDE ACT (OODA) LOOP MODELING

Modeling was done on to show the BMD functional loop with and without the DARBC. Reaction time to a hostile ballistic missile threat was modeled in an attempt to show the benefit of having the DARBC as part of the overall BMD system. This effort is the first attempt to quantify the time saved by employing the DARBC.

APERSTRUCTURE HULL INTEGRATION

Limited research was conducted regarding the conceptual layout of the OA elements on a generic ship platform in an attempt to visualize how the Aperstructure concept would come together. Considerations for the environment were taken into account. Also, the minimum size of the platform required to field the OA was determined using data from the Array Density Requirements research.

SHIP FLEXURE

The topic of ship flexure was addressed to quantify how much the aperstructure could flex due to the environment and to come up with an error budget for flexure as related to radar beam-forming performance. Based on the error budget as compared to the actual values of possible flexure, a recommendation for an auto-alignment requirement for the elements is discussed.

WIRELESS COMMUNICATION

Data from the T/R elements needs to be passed to a central computer for processing. With the concepts of the OA and Aperstructure, a great deal of cable would be required between the thousands of elements and the central computer. In an effort to reduce weight, and overall system complexity, wireless communication within the host platform was investigated.

COOLING

Based on the element power of the DARBC, cooling would be required to keep the system operational. Investigations into the methods used for cooling along with a look into different materials and their characteristics were conducted.

ELECTRONIC ATTACK (EA)

A side thought to the DARBC concept was to determine if the system, as designed to meet the BMD and counter stealth requirements, would be capable of being used as an EA weapon. The ideas ranged from using the DARBC for jamming or deception of enemy communications to firing Electromagnetic Pulses (EMPs) at enemy electronic equipment.

BUDGET & LOGISTICS

A combination all requirements led to the research of how the system could be supported so that system availability could remain at an acceptable level. Also, tradeoffs between requirements and cost were discussed. An overall acquisition strategy for the DARBC was developed as part of this study.

CONCEPT OF OPERATIONS SUMMARY

The DARBC radar will provide long-range search, detection and track of the various types of ballistic missiles for cueing to other organic sensors or sensors and systems in the overall Joint Battle Management Command and Control (JBMC2) network. The radar will provide early detection of ballistic missile launches over large areas of land or sea space not currently or adequately covered by existing sensors. Ships configured with DARBC will be

forward deployed to positions where they have greatest potential for detection of launches. Early detection and tracking increases overall engagement timeline, providing more time for decision making, weapon assignment, and weapon engagement from the overall BMD family of systems. Early detection using forward based sensors permits engagement of ballistic missile threats during boost and ascent phase when the threats are slower, larger and easier to engage.[lxii] The early detection, track and cueing will improve engagement by other BMD systems that engage the threat in midcourse or terminal phases of flight. Deployment of the ship to provide midcourse and terminal search, detection, and tracking of ballistic missiles is possible as well. Secondary threats that the radar will support search, detection and track of are stealth air threats. Detection of these threats will be at ranges where they pose a direct threat to the ship or units in the immediate operation area either by launch of weapons or as weapons themselves. The radar also provides capabilities to support UHF communications either in line of sight or by SATCOM link.

BMD MISSION

BMD is best accomplished using a layered defense/combined arms approach. There are too many threats in existence to rely on hard kill defenses only. Many countries can launch multiple salvo threats and from many locations. The best overall strategy will entail systems to attrite enemy capability using Information Operations (IO) / Electronic Attack (EA) / Strike in addition to hard kill of threats in flight. Current Navy BMD capability is based on the STANDARD Missile 3 (SM-3) launched from AEGIS ships. Depth of fire with SM-3 is limited during an engagement from one platform– generally one, max of two[lxiii]. Maximum effectiveness of AEGIS and SM-3 can be achieved when reaction time is improved by cueing SPY-1 and positioning the AEGIS platform for an engagement and allowing other sensors to be positioned for early detection and cueing. Detection of ballistic missiles can be enhanced from prior knowledge of launch location, time and target type. When intelligence can provide some of this information, especially location, specific search patterns can be generated to increase probability of detection. Space based assets can monitor large areas and cue sensors when launches have been detected. As a forward deployed combatant, the ship will potentially be exposed to direct attack by the state posing the ballistic missile threat. The ship and radar will be able to counter threats of anti-ship cruise missiles through hard kill methods. The radar design and ship integration shall enhance signature reduction of radar cross section (RCS) and Infra Red (IR). The ship/radar will be available on station for long periods of time regardless of weather and sea conditions. When ship is positioned to defend a terminal position, the radar must be capable of detecting the threat at ranges suitable for terminal engagements. These threats include re-entry vehicle (RV) as well as the associated debris and decoys of the threat.

THREAT SUMMARY

The Radar will be deployed in one of two basic scenarios. The first is to be forward deployed near a projected threat country or area positioned to search for ballistic missile launches. The second is a homeland defense position where the ship will be positioned to detect sea based launches from submarines or undisclosed threat surface ships. The forward deployed scenario could put the ship in a position where it is in harms way. Because the time line between detection and engagement is very short, shooters, armed with very fast interceptors or lasers,

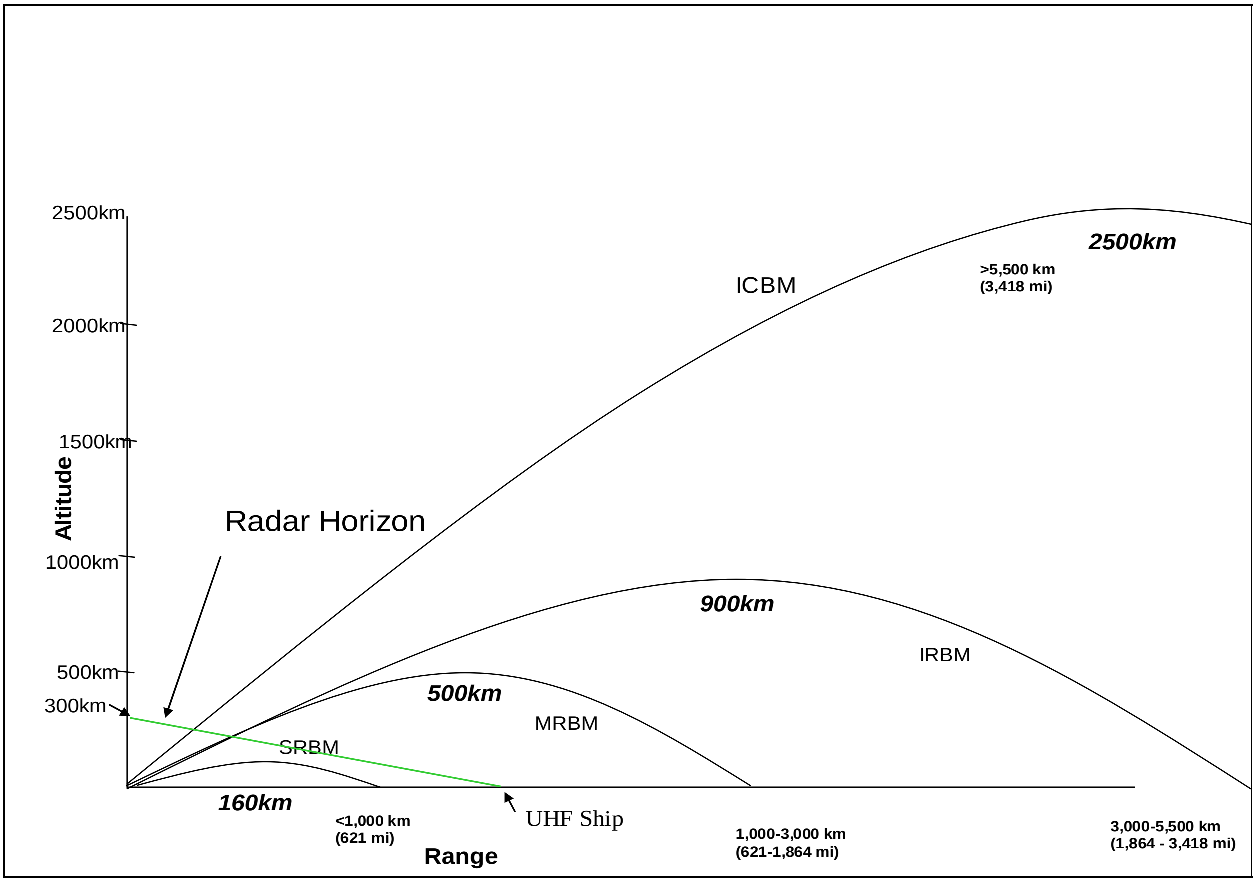
must be stationed close to the launch location. The proximity of this position to the threat means the ship is subject to attack. The ship will be subject to the same threats posed to current and future surface combatants such as Anti Ship Cruise Missiles (ASCMs) and other air, surface, and subsurface threats. The ship can be expected to be deployed and positioned for long periods of time while on station providing surveillance.

The ship/radar would normally be operated in conjunction with other BMD units. These units could be Patriot or Aegis platforms providing terminal phase defense. Where long-range ballistic missiles are launched, BMD fixed assets in Alaska or CONUS will be cued to support mid course tracking in support of Ground Based interceptors or other engagement means.

Ballistic missiles have proliferated over the last four decades and are now prevalent across the globe with over 24 countries capable of launching some form of this threat. As an example, over 100 foreign ballistic missile launches occurred around the world in 2004.[lxiv] Many countries also have capability to configure these missiles with Weapons of Mass Destruction (WMDs) including nuclear, chemical and biological payloads. Additionally submarines can launch Ballistic Missiles dramatically increasing threat launch areas increasing surprise and need for sensors with increased capabilities and search volume. Ballistic Missiles are classified in the following 5 main categories as described by the following table.

Ballistic Missile Category	Maximum Range	Apogee
Short-range ballistic missile (SRBM)	<1,000 km(621 mi)	160 km
Medium-range ballistic missile (MRBM)	1,000-3,000 km (621-1,864 mi)	500 km
Intermediate-range ballistic missile (IRBM)	3,000-5,500 km (1,864 – 3,418 mi)	900 km
Intercontinental ballistic missile (ICBM)	>5,500 km (3,418 mi)	2500 km
Submarine-launched ballistic missile (SLBM)	Any ballistic missile launched from a submarine, regardless of maximum range	Varies

Ballistic Missile Flight Path Characteristics



Ballistic Missile Flight Paths

The range and apogees reported are examples of maximum capabilities. Trajectories can support shorter ranges with lower or depressed apogees. Some may fly a trajectory that has a lower apogee to achieve maximum range. A ballistic missile is a projectile that has been given some level of initial power, operates within the earth's atmosphere or the immediate space above the atmosphere, and follows a path governed mainly by the laws of gravity. Notional trajectories for the above categories are depicted in the following figure.

Tactics for deploying these threats will involve surprise. Submarine launched threats are based on a stealthy launch platform that can hide its position and intent until after weapons release. Many BMD threats are launched from Transportable Erectable Launchers (TEL) that can hide their position until desired and then erect and launch in just a few minutes. TELs can virtually be hidden within the boundaries of an entire county. ICBMs are generally housed in silos that have generally known positions. While the probably known location of these launchers may help in destruction once rules of engagement permit, initial launches in an unprovoked attack can be achieved with little to no warning.

PROGRAM SUMMARY

Program strategy will be to develop class of ships that utilize the DARBC concept as a primary design driver and the capabilities as a primary mission function for the ship. The range capabilities of the radar provide order of magnitude capability over existing sensors along with the ship integration benefits of stealth ship design provide capabilities that need to be matched to a unique ship development. Initial Operational Capability will be reached when one DARBC ship is fully tested and delivered to the fleet to support a homeland defense mission. Full capability will be reached when sufficient ships are available to meet forward presence missions in two hazard areas and homeland defense missions on both east and west coast simultaneously. Future capabilities of the radar beyond those addressed in the initial fielding are not in the scope of this CDD. Planned spiral development of prototypes to reach initial capability is described.

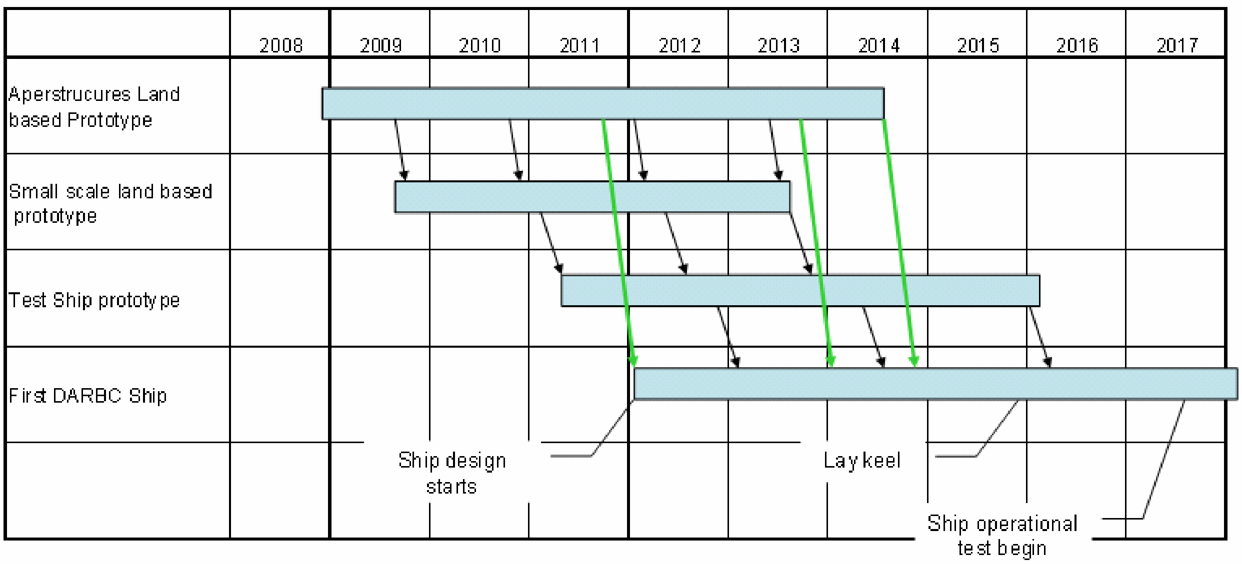
The development of DARBC has a number of technical risks associated with it that will be reduced through a series of prototype developments and evaluations. Since the radar design and subsequent ship integration of the aperstructure concept are considerably more extensive than typical sensors, a mature design of the radar is required prior to ship design. A longer than typical development period will be used to reduce risks and lower over all future ship development time and costs. This is a concept that has been used before where the Norton Sound (AV-1) was used to proof concepts, design and performance of the SPY-1 Radar prior to Aegis cruiser initial construction. Primary design areas that will be assessed using shipboard prototypes will be:

- Wireless communication of radar elements
- Beam formation and control in a random dispersed radar array
- Collection of performance information to be used in development of and verification and validation of models
- Impact of ship flexure on performance and on evaluation of methods to measure flexure and compensate for.
- Aperstructure ship integration
- Cooling

Prototype development will be centered on reducing known technological risk areas identified above and identifying new risk areas. Three primary prototype configurations will be employed and are:

- Land based prototype for aperstructure integration. This will be accomplished on a small scale. Array elements will be integrated into composite deck material and evaluated for performance of individual element transmit and receive sensitivity. The prototype can also be used to evaluate radar cross-section and infrared signature impacts of the design. Array element design and performance parameters will be used to help scale the other prototypes. Antenna array design will be used if possible in the ship integration prototype.
- Land based prototype for early development of a dispersed array in a controlled environment. This prototype will be used to provide early design concept validation. This prototype will be a small scale (e.g. ¼ size), and will not be used to demonstrate

Key Performance Parameters (KPPs) such as maximum range detection. It will be used to demonstrate beam formation and wireless communications of elements. This prototype will be used a risk mitigation prior to ship based prototype for continued development and demonstration of beam formation and control in a dynamic at sea environment. Prototype will be ½ to ¾ scale and will be used to demonstrate many radar performance parameters but not to eventual IOC configuration parameters. Ship flexure impacts, seawater and ocean environmental impact such as corrosion, multi-path, ducting, will be assessed. Evaluation of supportability concepts and risks will be evaluated equally with performance. Impact to and from other UHF/VHF systems for interference will be assessed and mitigated including other ship and land based systems. This prototype will be used during BMD test events as a collateral test and will track threat representative targets. Test ship will not be evaluated for aspects such as radar signature. The radar may only be employed on one side of the ship to keep costs minimized. Notional schedule of the three prototypes and how they relate to DARBC ship design is shown in Figure 2.



Notional Schedule of Three Prototypes

Test & Evaluation will be dependant highly on Modeling and Simulation to keep scale and costs of prototypes minimized. M&S will be developed with the concept to support the program through its life cycle, and not just Development and Operational Test (DT/OT) periods. Testing will be accomplished to reduce design risks prior to ship development. This will include supportability requirements like maintenance, reliability, tactics, and operator interface in addition to performance.

Program strategy will emphasize design concepts that permit minimal manning requirements including remote maintenance and monitoring, Built-In Test (BIT) and calibration, reliable and fault tolerant designs.

SYSTEM CAPABILITIES REQUIRED FOR THE CURRENT INCREMENT

DETECTION RANGE

The DARBC system shall have the capability to detect the signal returned from a notional ballistic missile target characterized by a RCS of 10 m^2 RCS[lxv] at the handoff range of 748 km[lxvi] where the DARBC would likely cue the S-band radar in order to engage the threat with a signal to noise ratio sufficient to exceed the receiver's sensitivity threshold. The notional ballistic missile target described in this project is defined as having a 77m^2 RCS in the UHF band and a 146 m^2 RCS in the VHF band[14]. It shall provide a consistent, timely, and accurate and target information in any environmental conditions. This capability provides the ability to protect the nation against WMD attack and coercion; and to render an adversary's cruise and ballistic missiles ineffective.

PROBABILITY OF DETECTION

The DARBC system shall have 0.90 probability of detection on a notional ballistic missile target described in the section 6.1 at a range of 748 km.

PROBABILITY OF ACQUISITION

The DARBC system shall have 0.90 probability of acquisition on a notional ballistic missile target described in the section 6.1 at a range of 748 km.

TRACK ACCURACY

At the conclusion of the acquisition cycle, the DARBC shall be capable of providing position and velocity information about target. Azimuth and elevation shall be accurate within ± 0.5°. Range shall be accurate within ± 0.5 km. Velocity shall be accurate within ± 100 m/s.

THERMAL SIGNATURE

DARBC system is design for long range detection and is beyond the limitation of the thermal image technology that exists today. However, in the future if the technology is available, study will be conducted to evaluate the feasibility of insert this capability to the DARBC system.

RELIABILITY, MAINTAINABILITY, AND AVAILABILITY

DARBC system shall have met the reliability, maintainability, and availability under normal operating condition. The Reliability, Maintainability, and Availability values are referenced from an existing phased-array radar system Test and Evaluation Master Plan (TEMP) 124 for DDG 51 Guided Missile Destroyer document since the DARBC models phased array radar system functionality. The thresholds and objectives are the same. The operational requirements are listed in Key Performance Parameters table below.

Key Performance Parameter Table

(U) Key Performance Parameters			
Key System Characteristics	**Attribute**	**Development Threshold**	**Development Objective**
Detection			
	Detection Range	748 km	1000 km
	Probability of Detection	0.90	0.95
Acquisition			
	Probability of Acquisition	0.90	0.95
Track Accuracy			
	Azimuth Elevation Range Velocity	± 0.5° ± 0.5° ± 0.5 km ± 100 m/sec	± 0.2° ± 0.2° ± 0.2 km ± 80 m/sec
Reliability			
	Mean Time Between Operational Mission Failures (Hardware) ($MTBOMF_{hw}$)	(U) 130.0 Hrs	(U) 130.0 Hrs
	Mean Time Between Operational Mission Faults (Software) (MTBOMFsw)	(U) 25.0 Hrs	(U) 25.0 Hrs
Maintainability			
	Mean Corrective Maintenance Time for Operational Mission Failure (Hardware) ($MCMTOMF_{hw}$)	(U) 2.0 Hrs	(U) 2.0 Hrs
	Mean Corrective Maintenance Time for Operational Mission Failure (Software) ($MCMTOMF_{sw}$)	(U) 18 sec	(U) 18 sec
	Scheduled Maintenance Time Per 24 Hours	(U) 2.0 Hrs	(U) 2.0 Hrs
	Restoration Time (Max Time) (From Scheduled Maintenance)	(U) 10.0 Min	(U) 10.0 Min
	Restoration Time (Max Time) (From System Test)	(U) 3.0 Min	(U) 3.0Min

(U) Key Performance Parameters			
Key System Characteristics	**Attribute**	**Development Threshold**	**Development Objective**
Availability			
	A_o (Ballistic Missile Defense Mission Profile)	(U) 0.9	(U) 0.9

FAMILY OF SYSTEM AND SYSTEM OF SYSTEM SYNCHRONIZATION

Currently, there are no Joint Capabilities Documents (JCDs) which define requirements for the DARBC. The requirements for the DARBC are being developed as if other Joint systems will be online at the time that the DARCB achieves Initial Operational Capability (IOC). For this current increment the DARBC will only need to integrate with systems on board the ship which the DARBC is installed. For this increment, the ship would be responsible for sending data from the DARBC out to other systems external to the ship.

The ship system interfacing with the DARBC needs to be one capable of employing the aperstructure concept as well as the communication interface. The DARBC development must be synchronized with the development of a new construction USN surface combatant as the aperstructure is not the type of system that could be backfit onto existing classes of ships due to the high level of physical integration required. The DARBC must be heavily considered during the design of the platform. Data from the DARBC should be capable of interfacing with other organic ship weapon systems for this increment.

The DARBC will not be integrated as part of a weapons system therefore, the presence of a BMD capable weapon system or external communications system is required onboard the DARBC ship.

INFORMATION TECHNOLOGY AND NATIONAL SECURITY SYSTEMS SUPPORTABILITY

The DARBC system capabilities described by this CDD are concerned with radar functions. DARBC is anticipated to have secondary functions that can support communications in the VHF and UHF bands. An Information Support Plan (ISP) has not bee produced to describe these capabilities. Communications functions of DARBC are considered outside the scope of the CDD at present. DARBC operational requirements necessary to support information exchange for battle management Command and Control (C2) in a joint system of systems will be covered in the CDD for the DARBC ship and are outside the scope of this CDD. Any discussion concerning information technology and/or National Security capabilities is considered to be not applicable at this juncture. However, if at a later date a decision is made to upgrade the radar system to include these requirements, a CDD revision will include these requirements.

INTELLIGENCE SUPPORTABILITY

Intelligence support requirements are considered outside the scope of this CDD. While the DARBC is anticipated to have security requirements that will permit inputs on intelligence data to support radar search requirements (e.g. potential BMD launch locations, projected threats and flight profiles) the definition of these requirements cannot be supported within current distribution criteria. Any discussion concerning Intelligence Supportability is considered to be not applicable at this juncture.

ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (E3)

The DARBC radar system shall be mutually compatible and operate effectively in the at-sea electromagnetic environment. It shall not be operationally degraded or fail due to exposure to Electromagnetic Environmental Effects (E3). Radar system and subsystem performance requirements are specified in MIL-STD-464A and MIL-STD-461E (equipment and subsystem/system level) for all electromagnetic disciplines. Threat countries seek to degrade senor performance using spoofing and high-power jamming. DARBC will need to operate in a high threat environment operating close to threat countries in hostile Electronic Attack environment.

The DARBC radar system shall be required to comply with Department of Navy (DON) requirements for topside design and ship EMC certification in accordance with NAVSEA S9040-AA-GTP-00/SSCR Rev 4, Change 1. The DARBC radar equipment will comply with the applicable DOD, Navy, National, and International spectrum management policies and regulations and will obtain spectrum certification prior to operational deployment. DD Form 1494 will be submitted to the Military Communications Electronics Board Joint Frequency Panel.

The DARBC system shall meet E3 control performance requirements as specified is this document. E3 control shall minimize electromagnetic radiation to personnel, fuels, electronic hardware, and ordnance in accordance with DOD INST 6055.11, and NAVSEA OP3565 / NAVAIR 16-1-529. Radiation hazards breakdown into three categories: Hazards of Electromagnetic Radiation to Personnel (HERP), Hazards of Electromagnetic Radiation to Ordnance (HERO), and Hazards of Electromagnetic Radiation to Fuel (HERF).

The DARBC transmitter shall not produce electric fields exceeding the following level in accordance with MIL-STD-464A:

- Metallic: 10 V/m from 10 kHz to18 GHz.
- Non-metallic: 10 V/m from 10 kHz to 2 MHz, 50 V/m from 2 MHz to 1 GHz.

The DARBC system shall be electromagnetically compatible, given operating frequencies over the following frequency bands (216-225 MHz and 420-450 MHz) with its external RF Electro-Magnetic Environment (EME) such that its system operational performance requirements are met. The electric field from the DARBC shall not exceed the following levels for operation on flight, weather deck, and transmitter main beam during system operation.

Frequency Range

Frequency Range (MHz)	Flight Deck		Weather Deck		Main beam of Transmitter	
	Electric Field (V/m – rms)		Electric Field (V/m – rms)		Electric Field (V/m – rms)	
	Peak	Average	Peak	Average	Peak	Average
150 - 225	61	61	61	61	10	10
225 - 400	61	61	61	61	25	25
400 - 700	151	71	151	71	1940	260

ASSETS REQUIRED TO ACHIEVE INITIAL OPERATIONAL CAPABILITY (IOC)

The technology required to integrate the Digital Array Radar for Ballistic Missile Defense and Counter-Stealth (DARBC) system into a new and advanced ship design will require several years of Research and Development prior to achieving Initial Operational Capability (IOC) of the system. IOC is likely to depend largely on integration of the DARBC into either an existing development spiral of a ship construction program or into a new ship construction program. IOC for DARBC is projected for fiscal year 2019 or beyond. The following systems and capabilities will be required at IOC:

- DARBC radar integrated into a ship employing the aperstructure concept.
- Ship systems capability of supporting Joint interoperability sufficient to support a Homeland defense mission. Systems will need to receive track information and distribute across BMD network for Command and Control (C2). Cueing to other sensors is not required at IOC.
- Initial spares, documentation, and support infrastructure capable of supporting the maintenance concept described in section 6 of this CDD. An interim support concept using OEM or other organization is acceptable at IOC. Support includes remote maintenance and monitoring systems and personnel.
- Capability for static alignment and calibration of DARBC array. Capability can be either embedded in the radar itself or as a mobile support system located at the homeport.
- Interim training for ships force and any government infrastructure.
- Joint Infrastructure C2 capable of receiving track information from the DARBC ship. Associated tactics, doctrine and procedures to use and disseminate this information will be required. Cueing to BMD networked sensors is desired and anticipated but not required at IOC.

SCHEDULE AND IOC AND FULL OPERATIONAL CAPABILITY (FOC) DEFINITIONS

IOC will be reached when one ship configured with a DARBC system is fielded and delivered to the fleet. The development of the DARBC ship and its associated systems is not

under the scope of this CDD. The mission of the ship and capabilities that will be required beyond those provided by DARBC will have a direct impact on DARBC schedule. The IOC ship will only be required to support BMD search, detection and tracking in a homeland defense scenario. Development of ship self defense capabilities that permit the ship to be forward deployed will extend the ship development time and cost. Ship self defense in a homeland defense mission should be less strenuous. The ship must be configured with Command and Control (C2) systems to be capable of performing homeland defense mission of detection of ballistic missile launches against the continental United States (CONUS).

OTHER DOTMLPF AND POLICY CONSIDERATIONS

The policy considerations for the Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) associated with fielding the DARBC are addressed at a high level in this document. The doctrine for the DARBC includes publications, tactics, techniques, and procedures on how the radar will function on its own and in a system-of-systems environment. This doctrine will guide the way the military utilizes the DARBC system. Doctrine will be heavily influenced by the overall mission of the DARBC ship and associated weapons systems. A forward deployed DARBC tasked to engage ballistic missiles over a threat nation will apply a different set of rules of engagement than a homeland defense positioned ship.

The organizational reporting structure for the DARBC platform will be influenced by other platforms that may be operating in conjunction. A DARBC ship positioned for early detection of launch supporting engagement from other platforms will need an organization structure that supports ship positioning and launch considerations in addition to system that can pass track information. DARBC search areas can be optimized if threat sectors and types are known. Timely reporting of this intelligence information through the organizational elements is required to ensure effective use by DARBC to accomplish its mission.

DARBC training will be documented by a Navy Training System Plan (NTSP) and will cover all elements of instructor requirements, shipboard operator and maintainer courses, remote maintenance support personnel, and all hands on training including embedded training capabilities.

DARBC will apply Commercial Off The Shelf (COTS) equipment, military developed equipment, and Non-Developmental Item (NDI) to minimize development and procurement costs. Application of these items needs to consider life cycle cost and ability to meet key system capabilities such as reliability. Significant materiel costs and timing will be associated with the development and procurement of the DARBC ship platform.

The requirement for minimal manning will depend largely on availability of qualified personnel. The competencies, skills, and abilities of personnel must be established and known and be considered as a driver for design decisions. DARBC personnel requirements will consider all levels of operations and maintenance including shipboard, remote maintenance and depot.

Facilities for DARBC need to ensure infrastructure capabilities to meet unique design aspects of DARBC. The integrated hull structure of DARBC may impact ability of tugs to approach and interface with the ship in order to not damage array elements. Calibration and

alignment of the array elements may require unique design features at piers to allow direct visibility to antenna elements during radiation. Remote maintenance facilities will require bandwidth, trained personnel, and representative systems to assist in trouble shooting and repair recommendations so ships force is seamlessly supported 24/7. Pier facilities will need to be able to support DARBC such that aperstructures are not damaged.

OTHER SYSTEM ATTRIBUTES

Key cost driver risk areas for DARBC are anticipated as follows:

- Manning: DARBC will be developed using concepts that will support reduced shipboard manning. The distributed nature of the array elements will make maintenance functions difficult and time consuming. Having fault tolerant design that can support operations with reduced array elements due to failure, high reliability, built in test and remote diagnostics and support can drastically reduce the man-hours required for preventative and corrective maintenance.
- Reliability: A key tradeoff to reduce manning is improved reliability reducing the need for maintenance. Design for reliability and procurement cost for high reliability parts can drive costs up dramatically.
- Maintainability: Built in test and monitoring will be applied and information forwarded to remote monitoring and assistance center. Ships crew will be relieved of preventative maintenance and troubleshooting requirements. Corrective maintenance will be minimized and applied for critical failures only.
- Dynamic Radar-Ship alignment: The distributed array elements are anticipated in needing a dynamic compensation system for measuring ship flexure and providing real time feedback that can be used in dynamic correction of beam formation and alignment. This system has not been developed yet let alone tested in an integrated ship environment.
- Static Radar-Ship alignment or calibration of the entire array of elements will be complicated and labor intensive due to the large number of array elements. Unless calibration can be accomplished automatically, alignment of individual array elements will need to be as is done today in Combat System alignment. Ships today have a number of sensors and weapon systems where individual elements are compared to a ship reference point. Alignment of individual array elements in today’s sensors such as SPY-1, are accomplished during production. The SPY array face is aligned to the ship during production of the ship. For DARBC this integration of elements will take place only during ship production and will be time consuming when 1000+ elements are used.

PROGRAM AFFORDABILITY

DARBC program costs and projections of Life Cycle Costs are outside the scope of this CDD. DARBC provides mobile long range BMD detection and tracking capability. The total program costs of DARBC and development of the associated ship can be favorably assessed or compared against other sensor options. Purchase of multiple Aegis platforms would be required in order to obtain the same search volume and detection capabilities as a single DARBC.

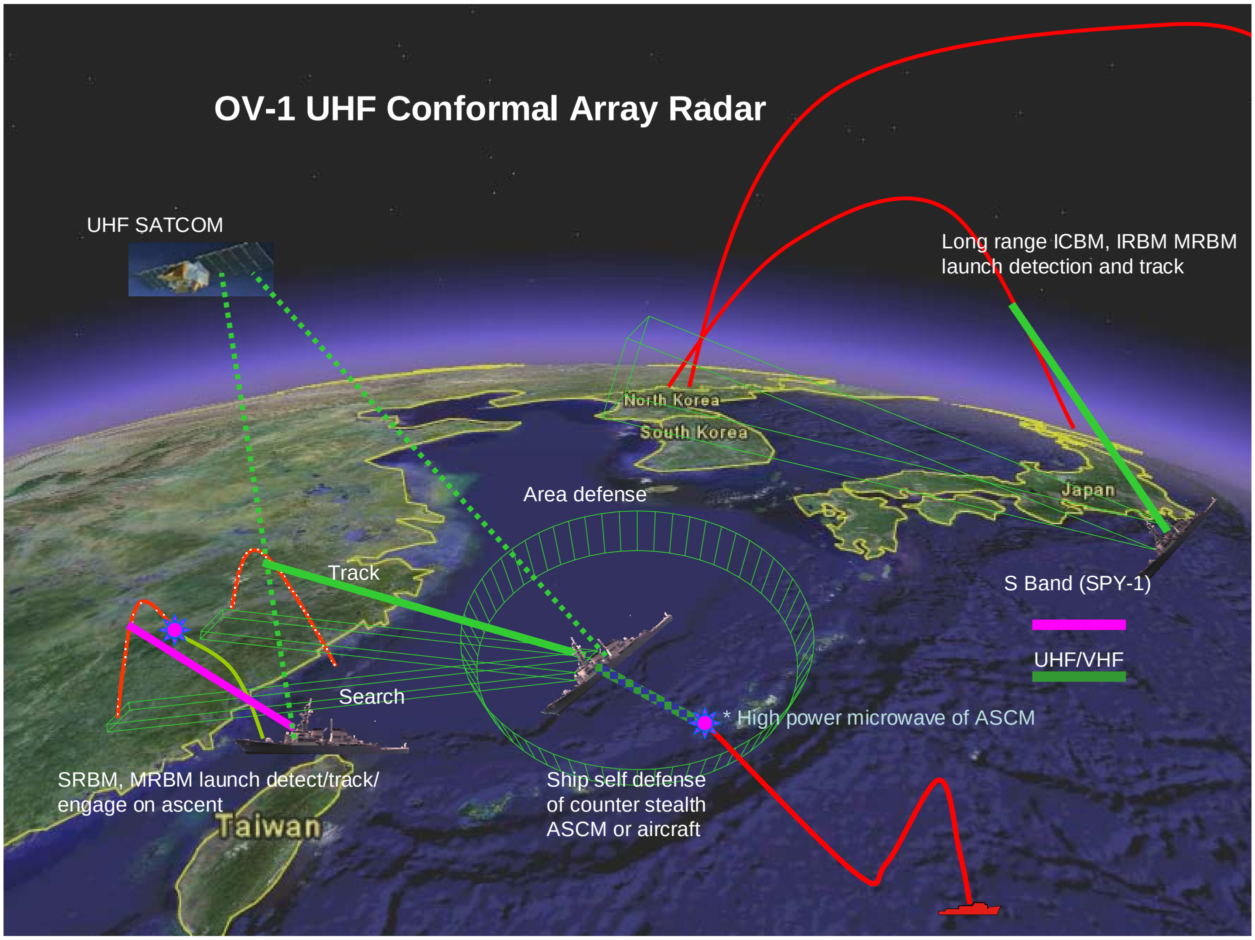
Ground assets would lack the range, mobility and would need to be deployed in multiple locations around the globe in order to achieve similar capabilities. Access to suitable land for ground based sensors may not be achievable from a political standpoint. Air assets would need to be purchased in significant quantities to achieve readiness levels for sustained coverage.

Appendix A: ACRONYMS

ACRONYM	DEFINITION
AD	Air Defense
AoA	Analysis of Alternatives
ASCM	Anti-Ship Cruise Missile
BA	Battlespace Awareness
BMD	Ballistic Missile Defense
C2	Command and Control
CJCSM	Chairman of the Joint Chiefs of Staff Manual
CONOPS	Concept of Operations
CONUS	Continental United States
CR #	Change Request Number
CSG	Carrier Strike Group
DARBC	Digital Array Radar for BMD and Counter-Stealth
DoD	Department of Defense
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities
DT/ OT	Developmental Test/ Operational Test
E3	Electromagnetic Environmental Effects
EA	Electronic Attack
EMC	Electromagnetic Compatibility
EMCON	Emission Control
EME	Electromagnetic Environment
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulses
ESAD	Electronic Safe and Arm Device
ESG	Expeditionary Strike Group
FOC	Full Operational Capability
FoS	Family of Systems
FP	Force Protection
HEL	High Energy Laser
HEMP	High-Altitude Electromagnetic Pulse
HERF	Hazards of Electromagnetic Radiation to Fuels
HERO	Hazards of Electromagnetic Radiation to Ordinance
HERP	Hazards of Electromagnetic Radiation to People
ICBM	Inter-Continental Ballistic Missile
ICD	Initial Capabilities Document
IO	Information Operations
IOC	Initial Operational Capability
IR	Infra-Red
IRBM	Intermediate Range Ballistic Missile
ISR	Intelligence Surveillance Reconnaissance
JBMC2	Joint Battle Management Command and Control

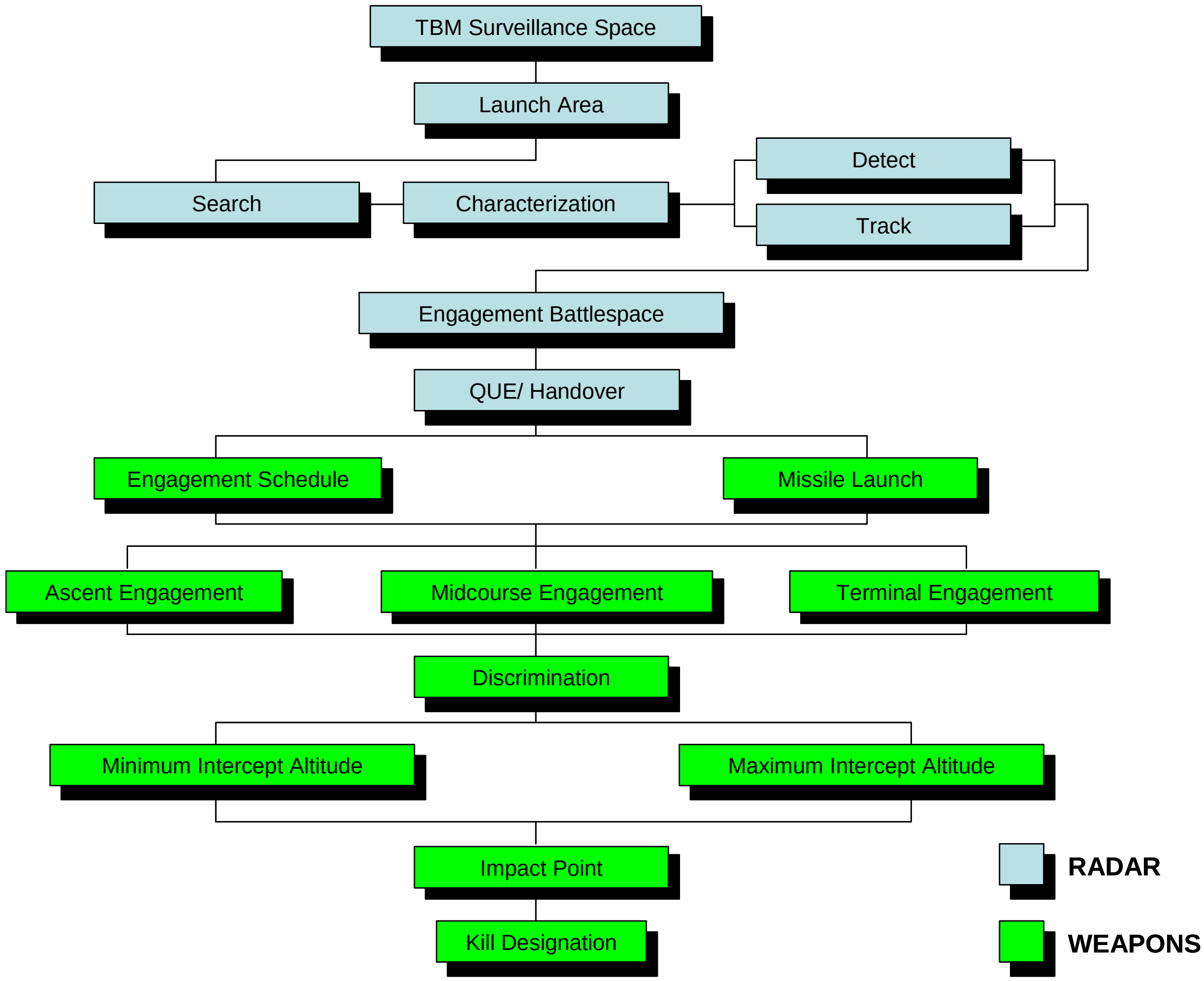
ACRONYM	DEFINITION
JFC	Joint Functional Concept
KEI	Kinetic Energy Interceptor
KPP	Key Performance Parameters
LORA	Level of Repair Analysis
LOS	Line of Sight
MHz	Megahertz
MRBM	Medium Range Ballistic Missile
NCOW	Network-Centric Operations and Warfare
OA	Opportunistic Array
OODA	Observe Orient Decide Act
OV	Operational View
RADHAZ	Radiation Hazard
RCS	Radar Cross Section
RV	Re-entry Vehicle
SATCOM	Satellite Communication
SLBM	Submarine Launched Ballistic Missile
SM-3	Standard Missile - 3
SPY-1	AN/SPY-1 Radar
SRBM	Short Range Ballistic Missile
T/R	Transmit-Receive
TBD	To Be Determined
TBM	Theater Ballistic Missile
TEL	Transportable Erectable Launchers
U.S.	United States
UHF	Ultra High Frequency
UJTL	Universal Joint Task List
USN	United States Navy
USN	United States Navy
VHF	Very High Frequency
WMD	Weapons of Mass Destruction

Appendix B: OV-1



OV-1 High-Level Operational Concept

Appendix C: OV-2



OV-2 Second Level Operational Processes

JOURNAL ARTICLE FOR THE DARBC

Authors

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NAVY DIGITAL ARRAY RADAR SYSTEMS ANALYSIS AND PARAMETER TRADEOFF STUDY

Abstract

United States Navy (USN) sources indicate a need for long-range shipboard radar for the Ballistic Missile Defense (BMD) program to augment and expand the USN's current capabilities. The Naval Postgraduate School (NPS) conducted a study on radar architecture research based on a digital Opportunistic Array (OA) integrated into a ship's hull.

The recently completed research defined the operational and technical requirements for the system, called the Digital Array Radar for BMD and Counter-stealth (DARBC). Initial analysis included characterization of the threat and definition of the Concept of Operations (CONOPS). Basic operational Key Performance Parameters (KPPs) were defined. Based on a notional ballistic missile Radar Cross Section (RCS), a radar technical parameters study derived the technical requirements for the radar necessary to meet the KPPs. Related research topics included radar parameter sensitivity, cooling, search pattern options, Electronic Attack (EA), ship flexure, topside array layout, supportability, and cost. Finally, reaction time modeling was conducted to quantify the increase in search volume and decision making time using the DARBC.

Introduction

The threat from ballistic missiles to the US and its allies is ever increasing in quantity and capability. The recent war in Lebanon has seen hundreds of small rockets launched into Israel. Had Hezbollah gained access to longer range missiles, much greater damage to property and loss of life throughout Israel could have occurred. North Korea flexed its military muscle on 6 July, 2006 with the test firing of seven ballistic missiles in one day, including a Taepo Dong II. While the failure of the dual stage Taepo Dong II, capable of reaching over 5000 kilometers into US soil, captured all the attention, the success of the other 6 missiles shows an increasing capability of this rogue nation. Ballistic Missile Defense (BMD) will be a common theme of military for years if not decades to come. "The Missile Defense Agency (MDA) mission remains one of developing and incrementally fielding a joint, integrated, and multilayered BMD system to defend the United States, our deployed forces, and our allies and friends against ballistic missiles of all ranges by engaging them in the boost, midcourse, and terminal phases of flight."[lxvii]

The paper explores a Very High Frequency (VHF) / Ultra High Frequency (UHF) ship-based Opportunistic Array (OA) radar, called the Digital Array Radar for BMD and Counter Stealth (DARBC), and describes the operational and technical requirements for this notional system. The combination of a large effective radar aperture

created by the OA and relatively low VHF / UHF transmit frequencies are expected to allow the DARBC system to achieve the long detection ranges needed by the MDA. These attributes may also provide the added advantage of being able to detect and track targets with low Radar Cross Sections (RCSs) such as stealth aircraft and missiles.

Scope

This project was based on tasking from the Naval Postgraduate School (NPS) in a proposal made to the MDA[lxviii] to provide a detailed radar systems analysis and parameter tradeoff study for a long-range VHF / UHF OA Surveillance Radar (OASR). The tasking further requested operational and technical requirements along with the resultant impact to ship. Discussions with faculty advisors provided initial assumptions which included limiting research on ship integration impacts. The project assumes that an aperstructure concept, or combination of radar aperture with ship's structure would be utilized and the DARBC radar would be implemented in a new ship design. Detailed integration and back-fit considerations were eliminated from the scope.

Concept of Operations

The DARBC radar will provide long-range search, detection and track of the various types of ballistic missiles for cueing to other organic sensors or systems in an overall Joint Battle Management Command and Control (JBMC2) network. The radar will provide early detection of ballistic missile launches over large areas of land or sea space not currently or adequately covered by existing sensors. Ships configured with DARBC will be forward deployed to positions where they have the greatest potential for detection of launches. Early detection and tracking increases overall engagement timeline, providing more time for decision making, weapon assignment, and weapon engagement from the overall BMD family of systems. Early detection using forward based sensors permits engagement of ballistic missile threats during boost and ascent phase when the threats are slower, larger and easier to engage. The early detection, track and cueing will also improve engagement by other BMD systems that engage the threat in midcourse or terminal phases of flight. Deployment of the ship to provide midcourse and terminal search, detection, and tracking of ballistic missiles is possible as well. Secondary benefits include search, detection and track of all stealth air threats. Detection of these threats will be at ranges where they pose a secondary threat to the ship or units in the immediate operational area either by launch of weapons or as weapons themselves. The radar also could provide tertiary benefits to support VHF / UHF communications either in Line Of Sight (LOS) or by SATCOM link.

The ship/radar would normally be operated in conjunction with other BMD units. These units could be Patriot or Aegis platforms providing terminal phase defense. When long-range ballistic missiles are launched, BMD fixed assets in Alaska or Continental United States (CONUS) will be cued to support midcourse tracking in support of ground-based interceptors or other engagement means.

Ballistic missiles have proliferated over the last four decades and are now prevalent across the globe with over 24 countries capable of launching some form of this threat. As an example, over 100 foreign ballistic missile test launches occurred around the world in 2004. Many countries also have the capability to configure these missiles with Weapons of Mass Destruction (WMDs) including nuclear, chemical and biological payloads. Additionally, submarines can launch ballistic missiles, dramatically increasing threat launch areas, escalating the need for sea-based sensors with enhanced capabilities in search volume. [lxvii]lxvii above Ballistic missiles are classified in five main categories as described by Table 2[lxix].

The ranges and apogees reported are estimated maximum capabilities. These weapons can support shorter ranges with lower or depressed apogees. Some may fly a trajectory that has a lower apogee to achieve maximum range. A ballistic missile is a projectile that has been given some level

of initial power, operates within the earth's atmosphere or exo-atmosphere, and after boost, follows a path governed mainly by the laws of gravity. Notional trajectories for the above categories are depicted in Figure . The DARBC Operational View (OV-1) is depicted in Figure . The output of the Threat RCS analysis concluded that a notional ballistic missile has a RCS of $10m^2$ when viewed by radar operating in the S-band. Assuming a fixed near-normal aspect angle of 88.4° which is based on the anticipated ballistic missile flight path characteristics relative to the DARBC ship, this notional ballistic missile had an equivalent RCS of $77m^2$ in the UHF band and $146m^2$ in the VHF band. These values aided in determining both operational and technical requirements for the DARBC. A Swerling Case of 0 (a non-varying RCS) was assumed for this initial analysis.

System Requirements Definition

One of the main KPPs for the DARBC was to quantify the required level of performance for the system. Based on the previous research, it was decided that the DARBC should have a single pulse Probability of Detection P_D of 0.90 at a range where the DARBC would cue another radar system (assumed to be a notional S-band fire control radar) for handoff and engagement. In order to determine the notional handoff range, a radar performance model was developed using Waterloo Maple® 7. It produced parametric plots of P_D vs. Range for a radar system with specified characteristics. Based on a notional set of inputs for characteristics such as power, effective aperture, temperature, receiver noise figure and noise bandwidth, parametric plots of a range of RCSs were graphed on a P_D vs. Range chart for the S-band radar. The basic equation governing this relationship between P_D and R_{MAX} is shown in Equation 1.

$$\frac{(\log_{10} P_{FA} - \log_{10} P_D)}{\log_{10} P_D} = \frac{S}{N} = 10 * \log_{10}\left(\frac{P_t G A_e \sigma n E_i(n)}{(4\pi)^2 k_b T_o B_n F_n R_{\max}{}^4}\right) \quad \textbf{(1)}$$

The handoff range was chosen to be the range where the S-band radar had a single pulse P_D of 0.5 for a notional ballistic missile (RCS of $10m^2$). This range was calculated to be 748 km as seen in Figure . Ignore the vertical lines on the plots as they are an artifact generated by Maple ® 7 when the values go to zero.

Based on the operational requirement for the DARBC to have a 0.90 P_D for a notional ballistic missile at a range of 748 km, further analysis, including tradeoffs and sensitivity studies were conducted on the radar technical parameters using the Maple ® tool. Along with this analysis, array density and basic Transmit / Receive (T/R) module layout research was conducted concurrently with the technical parameters analysis providing information such as T/R module spacing and quantity. The final analysis defined the technical requirements for the DARBC so that the system would be capable of meeting its operational KPP while keeping the numbers realistic. The final results of this collaborative effort showing the values for the DARBC as well as the notional S-band radar can be seen in `Table 3`.

Calculated System Performance

With the parameters above, the DARBC's anticipated level of performance was calculated. The DARBC KPP required a 0.90 P_D at this range of 748 km vs. the notional ballistic missile target (RCS of $146m^2$ for VHF and $77m^2$ for UHF) and the model showed that the DARBC is able to obtain 0.906 ≈ 0.91 using both VHF and UHF spectrums as seen in Figure   The power parameter is a conservative estimate of 500 kW. For that number of elements, the system may be capable of radiating at a much higher power level. Increasing the power would only increase the P_D values for the radar and the power was left at its current level in the Maple ® model. The graphs below show the anticipated performance of the DARBC using the parameters from `Table 3`. See `Figure` and `Figure` for the P_D vs. Range parametric plots for both the VHF and UHF frequencies for the DARBC. Based on these plots, the DARBC should have an effective range of approximately 2600 km.

Along with the CONOPS, RCS, aperstructure array density, topside layout, and radar technical parameters studies, other research was conducted which further defined the requirements for the DARBC. Results from T/R module cooling, ship flexure, Electronic Attack (EA), search pattern options, and budget and logistics studies can be found in the Joint Applied Project (JAP) Report for the DARBC, Naval Postgraduate School, September 2006.

Modeled System Benefit

With the technical parameters and calculated performance of the DARBC defined, the next major step in the research project called for the system to be modeled in an attempt to quantify the benefits of the system. The specific modeling goals were to calculate the extra volume covered and the extra decision making time with the DARBC as compared to the notional S-band system alone. The approach to accomplishing this took two specific routes.

The first model was a stochastic reaction time model using the Arena ® 10 process simulation software. The model was built with two baselines. The first one with the DARBC cueing to an S-band radar. The second was the S-band radar operating unaided. Both models had targets with uniformly distributed ranges, RCSs, and velocities with maximum and minimum values as seen in Table 4.

Also assumed in these models is that the target velocity is the closing velocity with respect to the ship. Initial detection time was collected based on a process simulation. For the model with the DARBC, if the target was generated at a position outside the maximum range of the DARBC (assumed to be 2000 km) then the target would not be detected until it closed to within that range limit and the detection time process was complete. If the target was generated inside the detection range, the detection time was assumed to be time of completion of the detection time process. If the target RCS was less than that of the notional ballistic missile, then the target was not detected. As the target closed on the handoff range, an engagement process simulation occurred which considered target acquisition, time to establish a fire control track, identify the target, compute the firing solution, grant permission to launch a missile, process launch sequence, and launch the missile. The total time from initial detection to the time of missile launch was measured during each run and over an average of 10 runs. This was done for both models.

The BMD system equipped with the DARBC has approximately 53.5% more time to respond to the threat than the system without the DARBC, specifically the DARBC lets you have 16.2 seconds versus the stand-alone S-Band system's 10.5 seconds.

The second reaction time model was done using Microsoft ® Excel and applied a more complex 2 degree of freedom target flight path. The more complex flight path allowed for the reaction time to be more accurately quantified in the time domain. The model varied the distance between the radar and the launch point of the ballistic missile, effectively varying how far forward the DARBC and S-band radar systems were deployed. Time-range plots for significant launch ranges of SRBMs, IRBMs, and MRBMs were generated, providing the time and area coverage benefits possible for each type of ballistic missile.

The model assumed a constant velocity of 7.5 km / s around the entire elliptical flight path unlike the real threat where the ballistic missile is significantly slower during boost and ascent phases. The model assumed a flat, non rotating Earth. The model only considered a flight path, where the TBM flies directly over the DARBC and S-band radar. Overall, the model provides a good basic estimate for the benefits of evaluation time and extra area coverage for short, intermediate, and medium-range TBMs as the assumptions make this a more conservative model.

Figure shows a flight profile of an IRBM at a launch range of 1200 km. The DARBC and S-

band radars are assumed to be located at the origin on the flight profile (top plot). On the lower plot, the top horizontal line represents the maximum DARBC detection range of 2000 km. The middle horizontal line represents the handoff range between the DARBC and the S-band radar. In this scenario, the IRBM would have never been detected had the S-band radar been functioning alone as seen when the target range to sensor never gets within the maximum detection range of the stand alone or "Un-aided" S-band radar represented by the lower horizontal line.

Final results of the Excel DARBC reaction time model are listed as follows:

For the SRBM, the DARBC provides:

- Up to 22 seconds of additional engagement time at a launch range of 400 km
- Up to 28 seconds of additional evaluation time at a launch range of 900 km
- Increased coverage from 400 km to 900 km launch range

For the MRBM, the DARBC provides:

- Up to 96 seconds of additional evaluation time at a launch range of 1200 km
- Increased coverage from 300 km to 1200 km launch range

For the IRBM, the DARBC provides:

- Up to 182 seconds of additional evaluation time at a launch range of 1300 km
- Increased coverage from 300 km to 1300 km launch range

This showed that the DARBC can add up to 3 additional minutes for decision making and engaging the threat while covering an additional 1000 km in range.

Conclusion and Recommendations

This research project concluded that the OA concept as defined by the DARBC operational and technical requirements has the potential of providing a very real and significant benefit to the USN and BMD program. More research is required in the areas of ship integration as these topics were barely addressed by this research project.

Future modeling efforts could be improved by incorporating the benefits of both system performance models together along with the addition of more realistic parameters such as a 3 dimensional flight path, varying target speed, Earth's curvature & rotation consideration, and environmental effects.

The model should combine and expand on the aspects of the two reaction time models, providing a more threat representative 6^{th} degree of freedom threat flight profile for various ballistic missiles.

Future RCS modeling should be conducted considering more realistic Swerling Case scenarios, varying aspect angles, and should all be stochastic. Stealth target RCS analysis should be incorporated into future studies in order to determine the effectiveness of the DARBC in the counter-stealth role.

Radar propagation analysis could be conducted including environmental factors such as ducting and various weather conditions.

Acknowledgements

We would like to acknowledge our project advisor Professor Mike Green for his guidance throughout the project, Professors William Solitario, David Jenn, Michael Melich, and Rodney

Johnson for their insight into the problem, Andy Summers from NAVSEA-05 for his thoughts concerning the integration of the Aperstructure, Ross Howard from NSWC PHD for his insight on ship flexure and error budget impacts, and lastly everyone in the group for their dedication to this project.

Ballistic Missile Category	Maximum Range	Apogee
Short-range ballistic missile (SRBM)	<1,000 km (621 mi)	160 km
Medium-range ballistic missile (MRBM)	1,000-3,000 km (621-1,864 mi)	500 km
Intermediate-range ballistic missile (IRBM)	3,000-5,500 km (1,864 – 3,418 mi)	900 km
Intercontinental ballistic missile (ICBM)	>5,500 km (3,418 mi)	2500 km
Submarine-launched ballistic missile (SLBM)	Any ballistic missile launched from a submarine, regardless of maximum range	Varies

Table 2 - Ballistic Missile Flight Path Characteristics

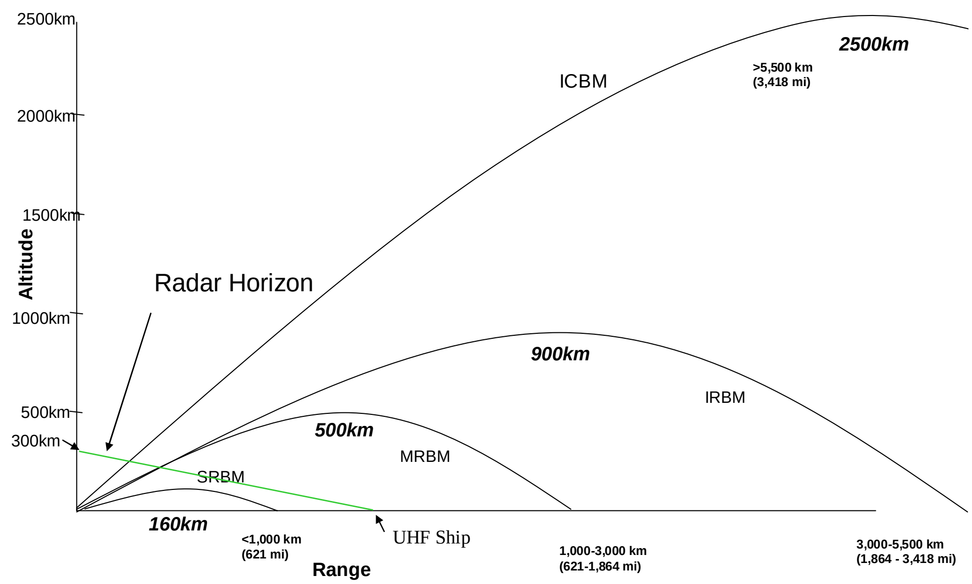

Figure 6 - Ballistic Missile Flight Paths

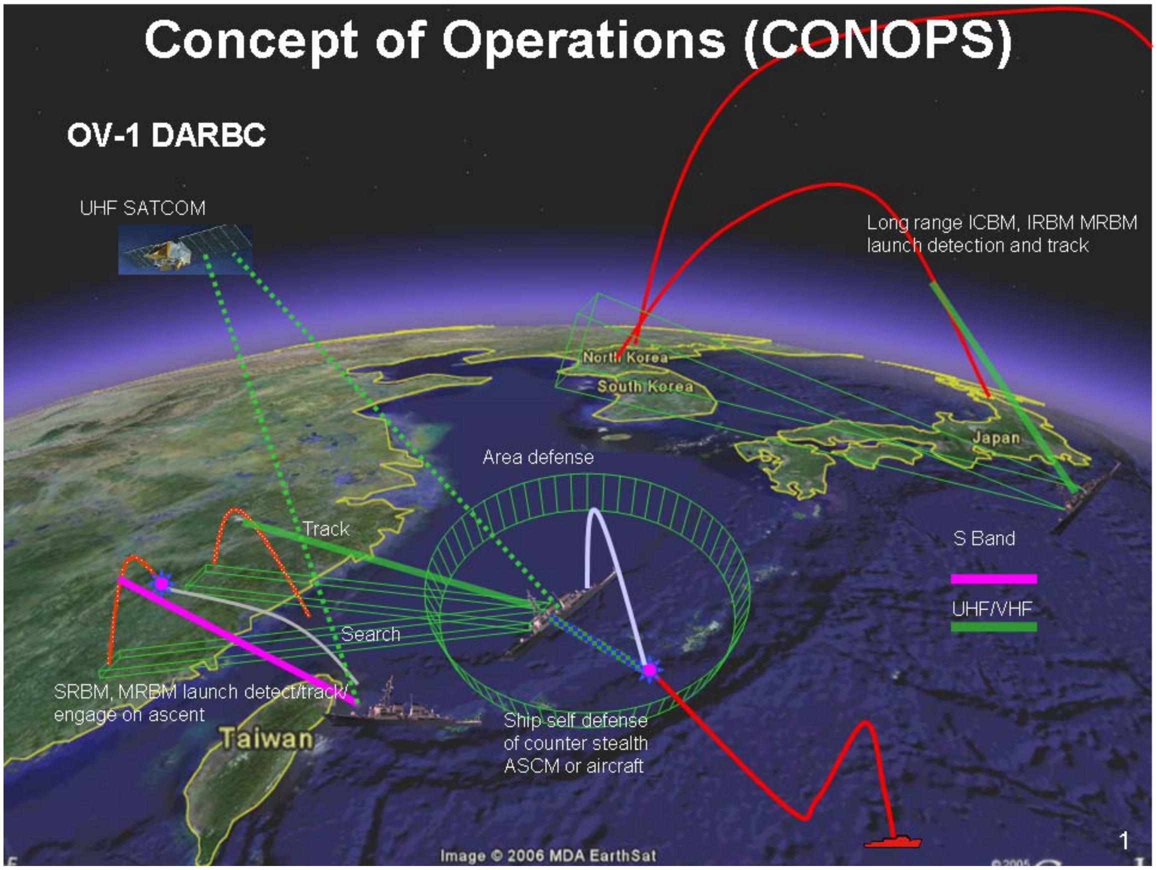

Figure 7- DARBC Operational View (OV-1)

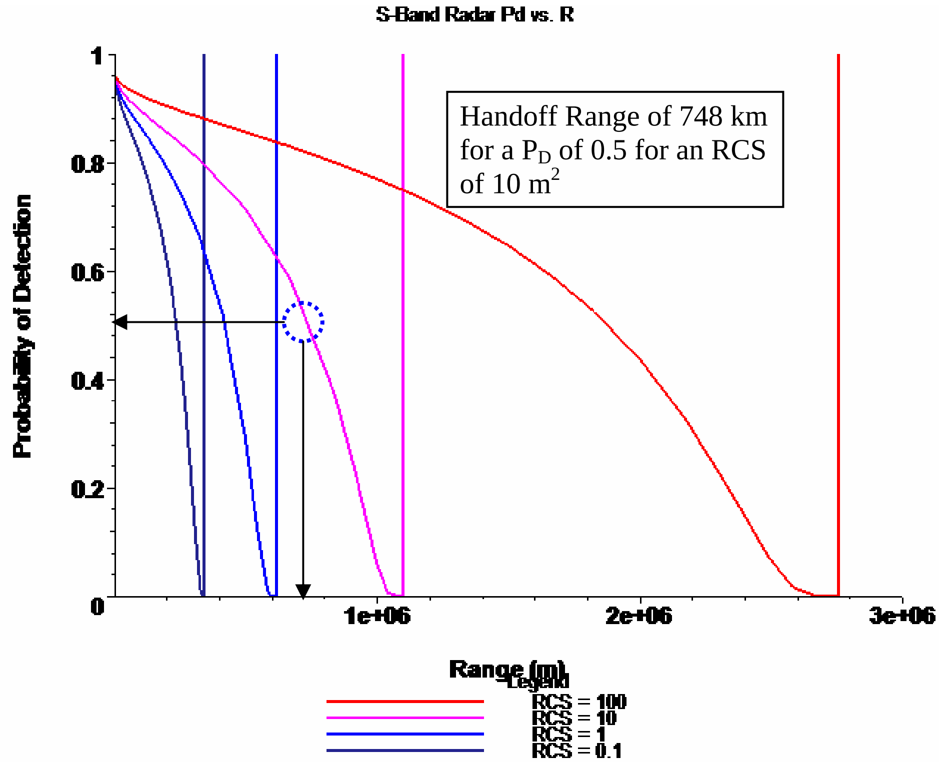

Figure 8 - Calculated Handoff Range to S-Band radar

Parameter	Description	Value Used
P_{max}	Transmitted power [W]	500 kW (VHF, UHF), 4 MW (S-band)
σ	Radar cross section of target [m^2]	146 (VHF), 100, 77 (UHF), 10, 1, 0.1 [m^2]
n	Number of pulses integrated	1
$E_i(n)$	Integration efficiency	1
k_B	Boltzmann's constant [J/degree K]	1.3806503E-23 J/ K
T_0	Standard temperature [degrees K]	290 degrees K
B_n	Receiver noise bandwidth [Hz]	23 kHz (VHF), 44 kHz (UHF), 4 MHz (S-band)
F_n	Receiver noise figure	$1\times10^{3/5}$ = 6 dB
P_{FA}	Probability of False Alarm	0.01
f	Radar Transmit Frequency	216 MHz (VHF), 420 MHz (UHF), 3 GHz (S-band)
η	Effective Aperture Efficiency	0.7

Parameter	Description	Value Used
n	Number of Array Elements contributing to 1 beam	3411
λ	Wavelength [m]	1.3879 (VHF), 0.7138 (UHF), 0.0999 (S-band)
A_e	Antenna effective aperture [m^2]	This is a function of n and η; 1193.85 (VHF & UHF), 17.5 (S-band)
G	Antenna gain	This is a function of A_e and λ; 38.9 dB (VHF), 44.7 dB (UHF), 43.4 dB (S-band)
S/N	Signal-to-noise ratio (SNR) required for detection based on a single pulse	Not directly calculated. This is a function of R_{max}.
R_{max}	Maximum radar range or detection range [m]	Variable (see plot)
P_D	Probability of Detection	Variable (see plot)

Table 3 - Radar Technical Parameters for DARBC and notional S-band radar

```
VHFPsubD:=evalf(eval(P4VHF,R1=748000),5);#VHF Pd at handoff range vs. Ballistic Missile (146m^2 RCS)
```

$$VHFPsubD := .90616$$

```
UHFPsubD:=evalf(eval(P4UHF,R2=748000),5);#UHF Pd at handoff range vs. Ballistic Missile (77m^2 RCS)
```

$$UHFPsubD := .90651$$

Figure 9 - Calculated output of Maple model for performance against a ballistic missile at handoff

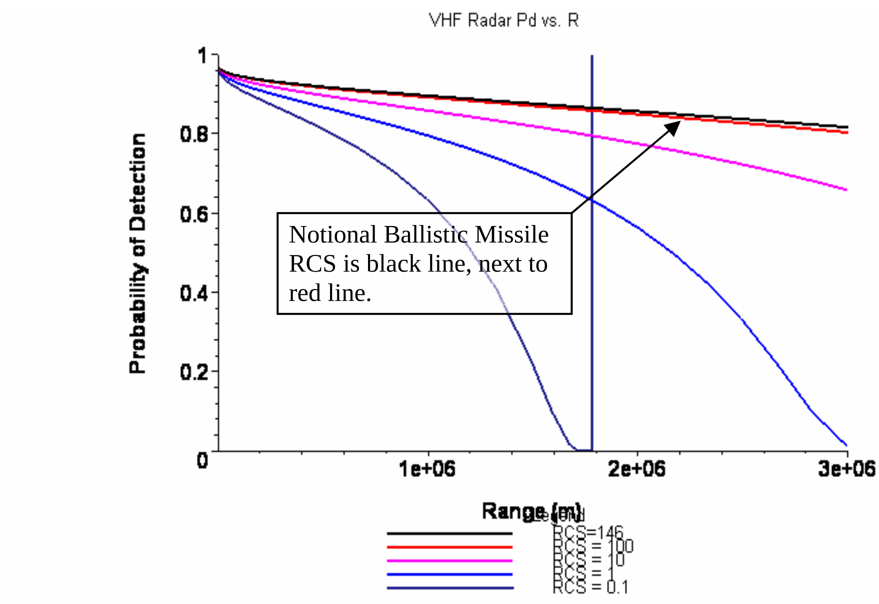

Figure 10 - DARBC PD vs. Range performance using the VHF spectrum

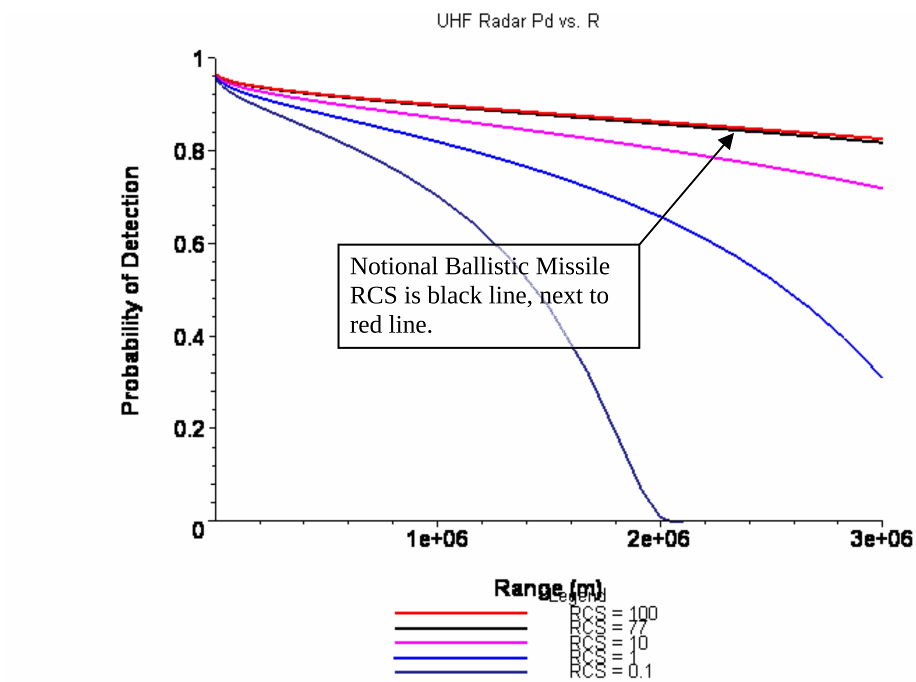

Figure 11 - DARBC PD vs. Range performance using the UHF spectrum

Parameter	Minimum	Maximum
RCS	$1m^2$	$300m^2$
Target Speed	1 km/s	10 km/s
Range from Ownship (DARBC aided)	500 km	5000km
Range from Ownship (local sensor only)	50 km	300km

Table 4 - Arena Model Parameters

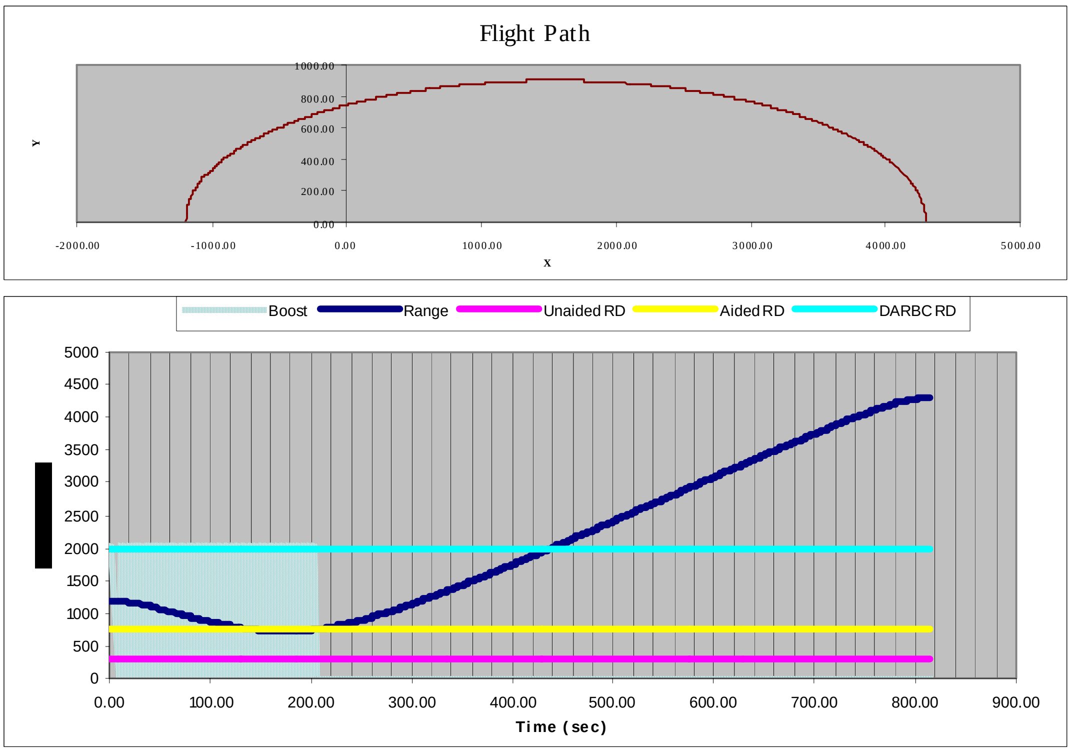

Figure 12 - Analysis of a flight profile of an IRBM launched 1200 km away from the DARBC

DARBC-TN-01 CONOPS

Document Technical Note	**Document** DARBC-TN-01
Program: DARBC	**Classification** Unclassified

TITLE: CONOPS for DARBC

PROBLEM STATEMENT:

A Concept of Operations (CONOPS) for the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-Stealth (DARBC) system is required to help define and articulate the Operational Requirements for this Opportunistic Array Surveillance Radar (OASR) system. The CONOPS is envisioned to be a tool to help TEAM R discuss and come to consensus on just when, why and how the system would be deployed and operated. The CONOPS should describe the missions of the Radar and identify any constraints envisioned by Radars design or employment including particulars of interfacing systems. The CONOPS would also be an early start to describing the threat and possible Key Performance Parameters (KPP) for Operational Requirements including identification of thresholds.

Expected Outputs of study:

Threat description

Presentation on CONOPS

OV-1

First Cut at Operational Requirements

Prepared by: Robert Hazle	**Original Date:** 9 April, 2006	**Comments:** Revisions incorporated 11
Reviewed by: Carla	**Date:**	
Reviewed by: Ian Barford	**Date:**	
Reviewed by: David	**Date:**	
Reviewed by: Paul Dailey	**Date:** 29-31 May, 19 Aug.	Document reviewed and comments made
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark	**Date:**	
Approved by: Professor	**Date:**	

PURPOSE

This Concept of Operations (CONOPS) for the DARBC system was developed to help define and articulate the Operational Requirements for this radar system. The CONOPS is envisioned to be a tool to help TEAM R discuss and come to consensus on when, why and how the system would be deployed and operated.

This TECHNOTE is comprised of the following sections:

I. Purpose: This section describes the purpose of the technote and its organization.

II. Background: This section provides information on key topics that must be understood in order to understand the operational requirements for the DARBC system.

III. Discussion: This section provides a CONOPS for the DARBC as well as a detailed description of the threat. This CONOPS describes the missions of the Radar and identifies any constraints envisioned by the Radar's design or employment including particulars of interfacing systems. The CONOPS also identifies how the DARBC will counter the threat.

IV. Conclusions: This section describes probable trade studies to be completed and recommendations for requirements to be included in the ICD.

Attachment 1: Ballistic Missile Description

Attachment 2: OV-1

References

It is generally the purpose of a CONOPS to represent the systems user's operational view for a system under development. This operational view is stated in terms of how a system will operate in its intended environment.

The most important step in the system development process is the accurate communication of operational requirements from those who need the system to those who will build it. As Systems Engineers often close to the development process we (Team R) need to be careful in our process of developing Operational Requirements. Problems we may encounter include:

1. We may not adequately convey the needs of the user.

2. We may describe requirements in terms of specifications describing attributes such as:

functions, performance factors, design constraints, system interfaces and quality attributes,

3. We may avoid describing terms concerning operational characteristics of the specified system such as:

classes of users and modes of operation

• normal mode • emergency mode • maintenance mode • backup mode • degraded mode

• diagnostic mode

essential needs, desirable needs – prioritized, optional needs – prioritized,

If we can accurately identify and prioritize user needs then we can provide the basis for establishing an incremental development process and making trade-offs among operational needs, schedule and budget.

I. BACKGROUND

A. number of resources and references has been generated in support of the overall Naval Postgraduate School (NPS) program in defining and developing a UHF/VHF OA radar. These studies and Theses have described many advantages and possible uses for the DARBC system. The Statement Of Work (SOW) and associated Theses concerning this OASR have been reviewed and proposed operational requirements identified and included in an overall assessment of operational needs.

II. DISCUSSION

The following is a general CONOPS Document for the VHF/UHF Opportunistic array radar

1. Scope. This CONOPS will cover the VHF/UHF radar for ship installation into a new class or combatant. The assumption used by the team and agree to by faculty advisors is to only look at a new platform class as opposed to looking at a backfit into existing platforms. This assumption is based on the use of an aperstructures hull integration concept that would not be backfit compatible. The platform would likely be a modification of the DDX class. Using DDX as a baseline assumption may be used for computations of array size or development of other options that impact radar design. The CONOPs scope will not be based on an assumption that the ship is armed with weapons that are capable of engaging Theater Ballistic Missile (TBM) threats and stealth air threats.

1.1 Identification. The VHF/UHF radar is multi-element "Digital Array Radar for BMD and Counter-Stealth (DARBC)". Its purpose is to search, detect and track TBM threats. It has a secondary purpose to search, detect and track stealth air threats.

1.2 System Overview. The Radar is an Opportunistic Array (OA) installed in ships over the ships superstructure including deckhouse and hull form to provide a very large radar aperture. The UHF or VHF frequencies and large aperture can provide significant performance in detection and tracking performance of Ballistic Missile threats at increased ranges over current phased array radars using C, S, L, or X bands. The radar requires no additional mast or structure for space and support helping to reduce ship RCS and overall size and signature. The array elements are integrated into the hull in an aperstructures (aperture/ structure) design concept described by references (a) and (b).

2. Threat Descriptions. Threats that the VHF/UHF radar would encounter would fall into the following general categories:

- Air Threats
    - Ballistic Missiles (Primary)
        - Short Range Ballistic Missiles (SRBMs)
        - Medium Range Ballistic Missiles (MRBMs)
        - Intermediate Range Ballistic Missiles (IRBMs)
        - Intercontinental Ballistic Missiles (ICBMs)
    - Anti Ship Cruise Missiles (ASCMs) (Secondary)
        - Subsonic Sea skimming
        - Supersonic Sea skimming
        - High Altitude
    - Aircraft (Secondary)
        - Stealth
        - Subsonic
        - Supersonic
        - UAV
        - Helicopter
- Surface Threats (Tertiary and only if radar has basic capability)
    - Large Ships

2.1 Ballistic Missiles. Ballistic missiles have proliferated over the last four decades and are now prevalent across the globe with over 24 countries capable of launching some form of this threat. Many have capability to configure these missiles with Weapons of Mass Destruction (WMD) including nuclear, chemical and biological payloads. Additionally submarines can launch Ballistic Missiles dramatically increasing threat launch areas, surprise and need for sensors with increased capabilities and search volume. Ballistic Missiles can be broken into 5 main categories as described by the following table.

Ballistic Missile Category	**Maximum Range**	**Apogee**
Short-range ballistic missile (SRBM)	<1,000 km (621 mi)	160 km
Medium-range ballistic missile (MRBM)	1,000-3,000 km (621-1,864 mi)	500 km
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Submarine-launched ballistic missile (SLBM)	Any ballistic missile launched from a submarine, regardless of maximum range	Varies

Table-1

The range and apogees reported are examples of maximum capabilities. Trajectories can support shorter ranges with lower or depressed apogees. Some may fly a trajectory that has a lower apogee to achieve maximum range. A Ballistic Missile is a projectile that has been given some level of initial power, operates within the earth's atmosphere or the immediate space above the atmosphere, and follows a path governed mainly by the laws of gravity. Notional trajectories for the above categories are depicted in the following figure.

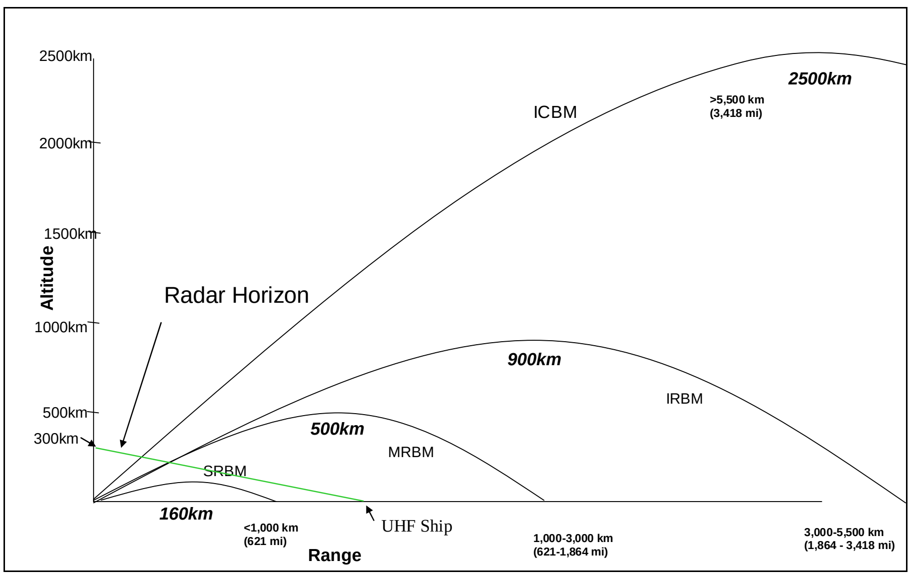


Figure 1. Ballistic Missile Trajectories

2.1.1. Launchers and Command and Control (C2). Ballistic Missiles can be launched from a variety of systems and platforms.

2.1.1.1. The most prolific is for Transportable Erectable Launchers (TELs). TELs are generally truck mounted for transportation to a launch location. They can be hidden in buildings or in geographical features such as trees and tunnels. The launch control is part of the truck system. Time to plan missions and achieve launch are dependant on factors such as the range, initialization requirements, mission planning requirements, and requirement to obtain launch permission but are probably on the order of

magnitude of minutes. The ability of sensors to locate a launcher prior to launch is very dependant on intelligence. The first indication that a ballistic missile has been launched will likely be a detection of the vehicle in flight. Placing a TEL on a commercial ship has been depicted as a potential scenario for engagement against the U.S. with SRBMs or MRBMs. This can complicate BMD capability requirements by requiring far greater number and location of assets to protect the U.S.

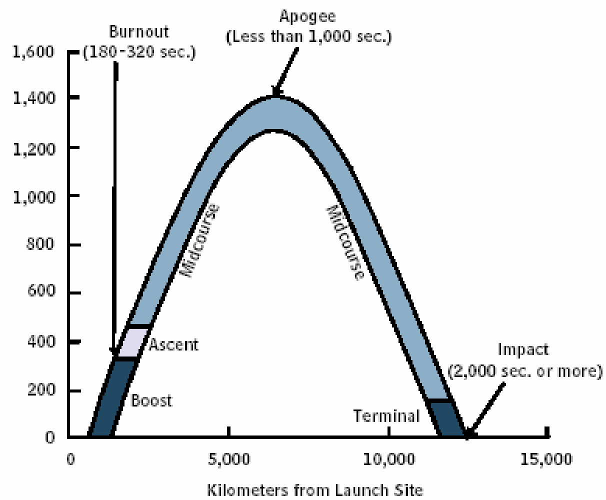
2.1.1.2 ICBMs and some IRBMs are very large and require substantial physical support and require storage in a permanent launch facility. These are generally protected facilities where the missile is stored in a silo. The permanent nature of a silo allows location of the site to be known compared to a TEL which can hide, move, and hide again.

2.1.1.3 A third launch capability is submarine launched. Submarines are a very stealthy platform and the sheer size of the world's oceans provides a great deal of space for hiding. Attacks against the U.S. from a submarine could greatly reduce flight time and reactions times from launches originating from countries across the globe. The ability to place a submarine over such a wide area makes locations of land based sensors and engagement systems inadequate for detection and engagement during boost phases.

2.2.2 Guidance methods. Ballistic Missiles often require various guidance methods in order to get close enough to the target so that payloads can meet their objectives. Payloads of mass destruction do not require accuracy associated with strike targets. Often cities and civilians are the targets where mass casualties can result. Sophisticated guidance methods are not required in these instances. Inertial, Global Positioning System (GPS) and GLONAS can provide sufficient accuracies. The path/trajectory of a Ballistic Missile includes three phases: a boost phase, a mid-course phase, and a terminal phase. These same trajectory phase names are used to describe the intercept phases and systems. Boost phase is the time period when the missile is given the thrust to reach its target. This period can last a few seconds or several minutes depending on the amount of thrust needed for the missile to travel to the target. The mid-course phase follows the boost phase, as the missile ascends to its highest point (the apogee) and then descends (via gravity) to its target. For Ballistic Missiles with a range of over 300 kilometers, the mid-course phase extends outside the earth's atmosphere (exo-atmosphere). If the missile has several stages, mid-course is also the phase in which the warhead separates from these stages and travels under its own inertia. This phase can last from a few minutes to up to 25 minutes. The final phase is the terminal phase, in which the missile or warhead re-enters the earth's atmosphere (endo-atmosphere), accelerates, and descends towards its target. It is the stage where the atmosphere affects the warhead and may cause unpredictable deviations to its previously predictable trajectory. This phase lasts less than a minute. The entire trip can take a few minutes or up to 30, depending upon the distance traveled. Figure 1 provides a notional trajectory and breakout of flight phases. This figure is from reference (c).

Trajectory of a Notional ICBM

(Altitude in kilometers)



Source: Congressional Budget Office.

Note: ICBM = intercontinental ballistic missile.

2.2.3 Payloads. Payloads or warheads consist of conventional high explosive, submunitions, chemical or biological warheads, or even nuclear warheads. Some missiles have multiple warheads capable of engaging multiple targets. This can cause significant problems for engaging as missiles would be required for each payload. Use of decoys amongst the actual warheads can cause problems for engaging missiles and systems. The decoys can draw weapons off the actual target and multiple objects whether real or decoy will cause a depletion of inventory. Payloads/warheads are called re-entry vehicles (RV) as they are the only portion of the many of the threat missiles to actually reach the target. They are considerably smaller in size and resulting Radar Cross Section (RCS) that the original missile. The choice of payload depends on the political will and objectives of the threat country and their technical ability to develop or to purchase. Any indentations to take over the area being engaged may preclude use of nuclear, chemical or biological weapons that would create problems for advancing troops. Ballistic Missiles can be used to cause severe devastation to break the political will and infrastructure of the engaged nation.

2.2.4. Propulsion. Ballistic missiles use from a single to triple stage motors. The motors are liquid or solid fuel and in some cases use liquid for first stages and solid for second and follow on stages. Choice of fuel depends on the size, and transportation needs of the missile and on range requirements.

2.2.5. Proliferation of threat. The threat faced from proliferating and evolving Ballistic Missile systems and associated technologies and expertise continues unabated. There were nearly 100 foreign ballistic missile launches around the world in 2004. This is nearly double the number conducted in 2003 and slightly greater than the number of launches in 2002. More than 60 launches last year involved short-range ballistic missiles, over ten involved medium range missiles, and nearly twenty involved land- and sea-based long-range ballistic missiles.[70]

2.2.6. Engagement of threat. The Missile Defense Agency (MDA) mission remains one of developing and incrementally fielding a joint, integrated, and multilayered BMD system to defend the United States, our deployed forces, and our allies and friends against Ballistic Missiles of all ranges by engaging them in the boost, midcourse, and terminal phases of flight.[71] Countering Ballistic Missile threats is a series of challenges requiring multiple integrated capabilities. Detection and tracking sensors are needed to see the missile. Computers are needed to calculate the missile's predicted trajectory and impact point and the interceptor's aim point. A significant technological challenge is to destroy the warhead. Intercepting the missile may prevent the warhead from reaching its intended target, but it does not necessarily destroy the warhead. It will fall somewhere, perhaps near the intended target or in some heavily populated area enroute to the target. The warhead needs to be destroyed. The best time to destroy a missile is during the boost phase when detection is easy, the missile is traveling at relatively slow speeds, and it is therefore most

vulnerable. Attacks in this phase offer the added attraction that the warhead (and the missile) may fall back into the shooter's territory, and therefore, there may be no need to worry about destroying the warhead. However, there are operational factors that complicate boost phase engagements. Because the time line between detection and engagement is very short, shooters, armed with very fast interceptors or lasers, must be stationed close to the launch location. Geography may not permit this. Even if geography does allow boost phase shooters to get into the right position to attempt the intercept, the sheer closeness of this position means that the shooters are subject to interception and attacks themselves. This creates its own set of self-defense problems for the shooter that may interfere with the Ballistic Missile engagement. Destroying the warhead in the mid-course phase also has challenges. The warhead needs to be destroyed and the real warhead must be distinguished from dummy warheads, empty stages, inter-stages, and other debris. This challenge is real and remains an issue except in terminal phase engagements when the atmosphere separates the real from the dummy warheads and other objects such as chaff, balloons, decoys, and makes identification easier. Over the years, people have suggested various ways to destroy the warhead in mid-course. These have ranged from getting close enough and exploding a large (i.e., nuclear) bomb, to throwing destructive debris (pebbles) in the warhead's path. The U.S. has settled on kinetic hit-to-kill technology (hitting a bullet with a bullet), which is now being built into U.S. systems. Destroying the warhead in the terminal phase presents its own set of technological challenges. As the warhead reenters the atmosphere it is affected by atmospheric friction, which may cause the warhead to twist and turn erratically at the most critical time of engagement (the end game). This complicates intercepts within this phase. This lack of predictability requires the interceptor to be highly maneuverable, to make rapid responses within the final seconds or milliseconds of the intercept, when both it and the warhead are moving at very high speeds.

2.2 Anti Ship Cruise Missiles (ASCMs). ASCMs have also been proliferated over the last few decades and can be launched from land, surface or subsurface vessels. Key characteristics of these weapons include their terminal speed and maneuver capabilities, RCSs, operating altitudes, payloads, seeker characteristics, and raid size when employed. Generally these weapons rely on stealth by flying low to avoid radar detection, having low RCS, using terminal maneuvers, speed, using passive seekers, or other techniques to avoid detection and potential for either hard or soft kill. These threats may be examined in further detail in future Technotes but are not the focus of this paper.

2.3 Aircraft. Aircraft generally pose a missile threat by launching ASCMs but can also be threats to ships as suicide attack or employ jamming, guns or other weapons that could harm a ship or friendly forces. They could also employ sensors that would provide unfriendly forces information about the location and operational status of naval forces. Attack aircraft could also employ stealth technology. The reduced RCSs that stealth technology gives could potentially be countered by the DARBC as the use of the VHF/UHF frequency bands would provide an enhanced ability to detect these targets over radars of other frequency bands. These threats may also be examined in further detail in future Technotes but are not the focus of this paper.

2.4 Surface Threats. Surface craft may launch missiles, or fire guns and Rocket Propelled Grenades (RPGs) to counter a ship. Suicide attacks are also possible. Navy ships are employing signature control techniques just as is the U.S navy to keep RCS and other signatures minimized. Small commercial craft by the nature of their design can produce small signatures and can be quite stealthy especially in sea states that create clutter and swells. Submarines while not surface threats do break the surface to obtain visual information or communications from periscopes. The submarine threat is so vital that periscope detection is a valued capability for any sensor. Surface threats will not be addressed in this paper nor are likely to be examined in future Technotes.

3. The Current System or Situation. BMD relies on a complex layered structure supported by all military services and involves some allied components. The system consists of a network of sensors, weapons and Battle Management C2. Sensors are a key element for detection, reporting, tracking and updating C2 for engagement systems. The short reaction timelines required to counter the threat depend on extremely accurate and timely information. In threat situations where launch locations can occur over large expanses of land or ocean, Navy assets will be limited in total area covered by current assets. Launches that occur deep inside a states' territory require Navy ships to get as close as possible to shorelines to provide deeper surveillance coverage, creating greater vulnerability to attack. AEGIS ships configured with SPY-1 radar must balance search for Ballistic Missile launch with surveillance around the ship for air

defense. Off loading BMD functions to another sensor would improve AEGIS time budget and coverage for Air Defense (AD) functions. Defense support system satellites provide spaced based surveillance and early warning detection of launch in IR and visible spectrums. These sensors provide track though mid-course flight and intercept.

Existing systems consist of the following:

• Ground-Based Interceptors located at Vandenberg Air Force Base, California and Ft. Greely, Alaska

• Upgraded Cobra Dane radar (Alaska)

• Upgraded Flyingdales radar (United Kingdom)

• Upgraded Beale radar (California)

• Sea-Based X-band radar (Alaska)

• Forward-Based X-band radar

• Aegis Long-Range Surveillance and Track Destroyers

• Aegis Engagement Cruisers

• Standard Missile-3 sea-based missiles

• Patriot Advanced Capability-3 missiles

• Battle Management Command, Control and Communications

3.1 Background, Objectives, & Scope. Per the reference (d) SOW, NPS has been discussing with MDA a United States Navy (USN) requirement for a very long range shipboard radar to support BMD surveillance, tracking, and discrimination functions. NPS has been working on a radar concept that could use the ships structure to support distributed antenna elements for a very large array antenna in UHF or VHF bands. NPS has included a team from the MSSE program at NSWC PHD, COHORT # 4 to participate in the project by developing, defining and documenting operational requirements. This CONOPS will attempt to describe operational requirements to meet the global objects of MDA. The NPS studies have also provided a good deal of potential additional capabilities that the VHF/UHF radar could support in addition to those described by the MDA. These capabilities cover additional threats beyond BMD and functions of the system for communications.

3.2 Operational Policies & Constraints. Current USN assets while quite capable are limited in numbers and sensor range. By the end of 2005 a total of 10 AEGIS DDGs and 2 CGs have BMD sense, track engage capability. Engage capability is limited by available SM-3 assets which are increasing in inventory. Deployment and positioning of ships must consider political situations and tensions as well as attack capabilities of our potential enemies. Increasing the search volume by extending range can help provide greater flexibility for coverage without violating international waters. The potential for sea-based threats either from submarines or mobile launchers placed on commercial ships increases threat launch areas and opportunities. Ground based sensors and ground based interceptors are limited in locations where they can achieve detections of Ballistic Missiles during early launch phases and engagements during boost phases. This means that engagements can only be accomplished during midcourse or terminal phases of flight where threat speeds are higher, RCS of the RV is low and multiple objects (RVs and decoys) may be present.

3.3 Description. The existing BMD system components consist of sensors, weapons and an integrated Joint Battle Management C2.

3.3.1 Sensors. BMD sensors are comprised of:

Existing Defense Support System Satellites – These can detect launches and provide tracking which leads to cueing to other sensors for engagement.

Upgrades to existing early warning radars at Beal Air Force Base in California, Shemya Alaska, and Flyingdales United Kingdom

Aegis Cruisers and Destroyers using the SPY-1 radar

Sea-based Terminal operating from Adak Alaska

Mobile operating station – Several of these systems are fixed sites that cannot provide early detection and tracking from launches on the Pacific Rim. The mobile terminal will be limited to land based locations that may be masked by range or terrain features.

The Aegis SPY-1 equipped ships are flexible in location but are limited in maximum search range by capabilities of the SPY-1. SPY resources must also be managed between search for ballistic missiles and search and track of other air and surface threats. The Sea based terminal is somewhat flexible for repositioning as a mobile platform but is not likely to be deployed in harms way. If it is not moved significantly from it's location of Adak Alaska, it will have similar constraints to that of the Shemya Alaska site.

3.3.2. Weapons. Missiles used for BMD are:

STANDARD Missile 3 (SM-3), which is capable against short and medium range threats in terminal and midcourse engagements.

Ground based mid course defense missiles which are capable against intermediate and long range missiles.

Patriot Advanced Capability (PAC-3) which is capable against short range missile and terminal defense missions.

A Kinetic Energy Interceptor (KEI) is in development and will be a future capability. A USN mobile interceptor is planned for integration in ships and possibly submarines. This weapon will provide engagement capability during boost and ascent phases. Providing sensor capabilities commensurate with the capabilities of this weapon will be necessary.

4. Justification for and Nature of Proposed Changes & New Features

4.1 Justification. The Ballistic Missile threat is proliferating in numbers, capabilities and potential for U.S. homeland defense from sea based firings from submarines and surface ships, potentially even commercial vessels. Current BMD capabilities lack forward based long range detection and tracking capabilities to assist in supporting mid-course engagements from ground based interceptors. Forward based long range sensors would help provide early waning and confirmation of launch from existing satellite systems. Current ship based sensors lack range capability for detection and track to support future ship based KEIs. These weapons would provide mobile boost and ascent phase engagements that would dramatically increase defended area and keep WMD payloads from leaving their country of origin. Future high energy weapons will provide even greater capability for engagements in boost and ascent phase, increasing need for long range sensor. Potential for sea-based launches of Ballistic Missiles increases need for ocean based surveillance. Long-range surveillance capability reduces quantity of assets required to cover sea based launches. Engagements with KEI missile or high-energy lasers would also help support engaging these threats. Long range sensors can support platforms close to enemy shores to improve boost phase engagements, but operating in Emissions Control (EMCON) to avoid detection.

5. Concepts of Operations for the New or Modified Proposed System

5.1 Background, Objectives & Scope. The objective of the DARCB is to be the major sea-based sensor for surveillance and tracking of Ballistic Missiles from launch through midcourse. The radar will be integrated with the overall BMD framework. The description of this framework and its capabilities are not in the scope of this paper or the capstone project. As capabilities of individual elements of this system and the overall BMD system are generally classified and are evolving it is not sensible to make determinations on individual capabilities. Rather assumptions will be made and sensitivity analysis about the assumptions will be used to address needs.

5.2 Description of Proposed System. The DARCB will be a ship-based radar with sufficient power, aparture and frequency (Operation at 216-225 MHz and 420-450 MHz) to provide long range search, detection and track of Ballistic Missiles from great distances. The ship will likely be a combatant equipped with a weapon of sufficient range and capability to provide boost and mid-course phase engagements of SRBM, MRBMs, IRBMs, SLBMs, and ICBMs. Standard radar design requirements, including frequency, bandwidth, peak and average power, aperture, beam width, main-lobe and side-lobe gains, scan coverage, pulse recurrence frequency (PRF), pulse width (PW), inter- and intra-pulse modulation, coherent and non-coherent processing gain, range / Doppler / angular resolution and accuracy, etc will be investigated. Capabilities for the radar are documented in other technotes under development by Team R.

5.3 Modes of Operation.

5.3.1 Volume Search. 360 degrees to elevation angle of 90 deg and a range of 2000 km. The radar will be able to continue volume search even while providing other search and track functions. Limitations may result in volume searched as function of time.

5.3.2 Horizon Search. Primary search mode of radar looking for Ballistic Missile launches during boost phase. Horizon search can be sectored when a threat is coming from a know location or direction.

5.3.3 Search on a Cue by satellite. Radar can search based on a cue from source such as satellite or other radar. Search scan will be dependant on the originating sensors known capabilities and limitations, time latency, and potential trajectories.

5.4.4 Fence Search. Fence search may be the primary mode used for detection of ballistic missiles during boost phase. In fence search a picket or constant scan is established across some sector such that any ballistic missiles launched that pass through this fence will be detected. The size and number of sectors will need to be managed to optimize use of radar resources. Fence search can be thought of as a from of horizon search. When threat locations are known, the fences can be set up to cover only potential threat locations. This requires reception of this particular intelligence data.

5.3.4 Tracking. DARCB

5.3.4.1 Active Monostatic tracking. Tracking of ballistic missiles will be required with sufficient accuracy in position and time to allow designation to other sensors. These sensors are assumed to be on the same ship and off the ship as part of the overall Ballistic Missile Defense system. The small RCS and high rate of speed of these targets will require some degree of accuracy. Tracking to support fire control in support of a missile engagement requires much tighter accuracy than cueing. Capability of DARBC to support this level of accuracy is questionable and may require new techniques in radar beam control and missile technology for sensors that can operate across a larger volume than exists today.

5.3.4.2 Passive Bi-static tracking. This includes operations for both the active emitter ship or location and passive tracking platform.

5.4 Capabilities. Radar will support exo-atmospheric functions. Functions are assumed to be search, track, discrimination, and handover of Ballistic Missile or its RV.

- Handover is assumed as a minimum to be to SPY radar as an additional organic shipboard sensor. Handover is not limited to SPY and not limited to same ship. Handover or other sensor cuing could also be done through a Joint communication system such as ForceNet which would take the role of sending the cue to other sensors or weapon systems.

- The DARBC Antenna may be able to support communications. An example could be a data link to another ship, UAV or other unmanned vehicle.
- Antenna may be able to support Electronic Warfare (EW) functions such as electronic attack.

5.5 Changes/Features Considered but Not Included. Operational requirements for a new ship based sensor are many as sea and air threats continue to evolve and improve. Requirements for missions outside of BMD are not considered in this paper.

5.6 User Classes

5.6.1 Organization Structures. DARCB will be installed in USN combatants with BMD missions. Operators maintainers of the radar will be Navy enlisted. Ships will have minimal manning so that radar maintenance and reliability requirements need to minimize labor for support. The radar will be very complicated and will require automated features for set up, calibration, maintenance and trouble shooting, fault isolation and diagnosis. Distance support features that allow off ship experts to support and analyze problems will be utilized.

5.6.2 Profiles of User Classes. It is assumed that these ships will have additional sensor(s) for tracking and fire control during engagements. Interoperability with other BMD sensors for engagements is also assumed. The DARCB will support cueing of other sensors including all existing sensors.

5.6.3 Interactions among User Classes.

6. Proposed Operational Scenarios

6.1 Forward Deployed DARCB detects SRBM/MRBM/IRBM/ICBM and cues an engagement with KEI round during ascent phase from the same platform.

6.1.1 Forward Deployed DARCB detects MRBM/IRBM/ICBM and cues an engagement with KEI round during Midcourse phase from the same platform.

6.1.2 Forward Deployed DARCB receives cue from Satellite for detection of SRBM/MRBM/IRBM/ICBM and cues an engagement with KEI round during ascent phase from the same platform.

6.2 Forward Deployed DARCB detects SRBM/MRBM and cues an engagement with SM-3 round during midcourse or terminal phase from the same platform.

6.3 Forward Deployed DARCB detects SRBM/MRBM and forwards track information to Aegis platform that engages with SM-3 round during midcourse or terminal phase.

6.4 Forward Deployed DARCB detects ICBM and forwards track information to Aegis/SM-3 platform, PAC-3, or ground based interceptor that engages in terminal phase or ground based interceptor that engages in midcourse phase.

6.5 Homeland defense deployed DARCB detects SRBM/MRBM or SLBM and engages with KEI round during boost phase or forwards track information for engagement during terminal phase.

7. Summary of Impacts

7.1 Operational Impacts. The DARCB provides early detection of all types of Ballistic Missiles in boost or ascent phases. This will allow engagements by existing and future sea-based weapons during boost/ascent phase where this would not be feasible today. The radar provides a large volume search area reducing numbers of Aegis based systems to support launch surveillance only. This supports homeland defense scenarios against sea-based launches from ships or submarines. This also supports forward deployed scenarios where this sensor can cue Aegis ships positioned to provide defended area coverage but not positioned well for surveillance and early initial track establishment for maximum time reaction.

III. CONCLUSION

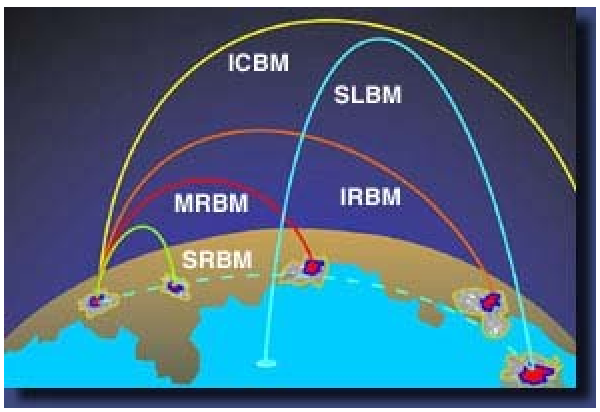
This section is not applicable to the CONOPS for this Technote.

Attachment 1: Threat Description Details

The information below was extracted from the following two web sites.

Reference: http://www.mda.mil/mdalink/bcmt/bcmt.html

National Air Intelligence Center
Wright-Patterson Air Force Base, Ohio
September 2000



Ballistic Missile Category	**Maximum Range**
Short-range ballistic missile (SRBM)	<1,000 km (621 mi)
Medium-range ballistic missile (MRBM)	1,000-3,000 km (621-1,864 mi)
Intermediate-range ballistic missile (IRBM)	3,000-5,500 km (1,864 - 3,418 mi)
Intercontinental ballistic missile (ICBM)	>5,500 km (3,418 mi)
Submarine-launched ballistic missile (SLBM)	Any ballistic missile launched from a submarine, regardless of maximum range


SS-21
SS-23
Iskander-E
SS-1c Mod 1
SS-1c Mod2
Al Hussein
Prithvi
Vector
Hatf-1
Shaheen
CSS-7
CSS-6
CSS-8
Al Samoud

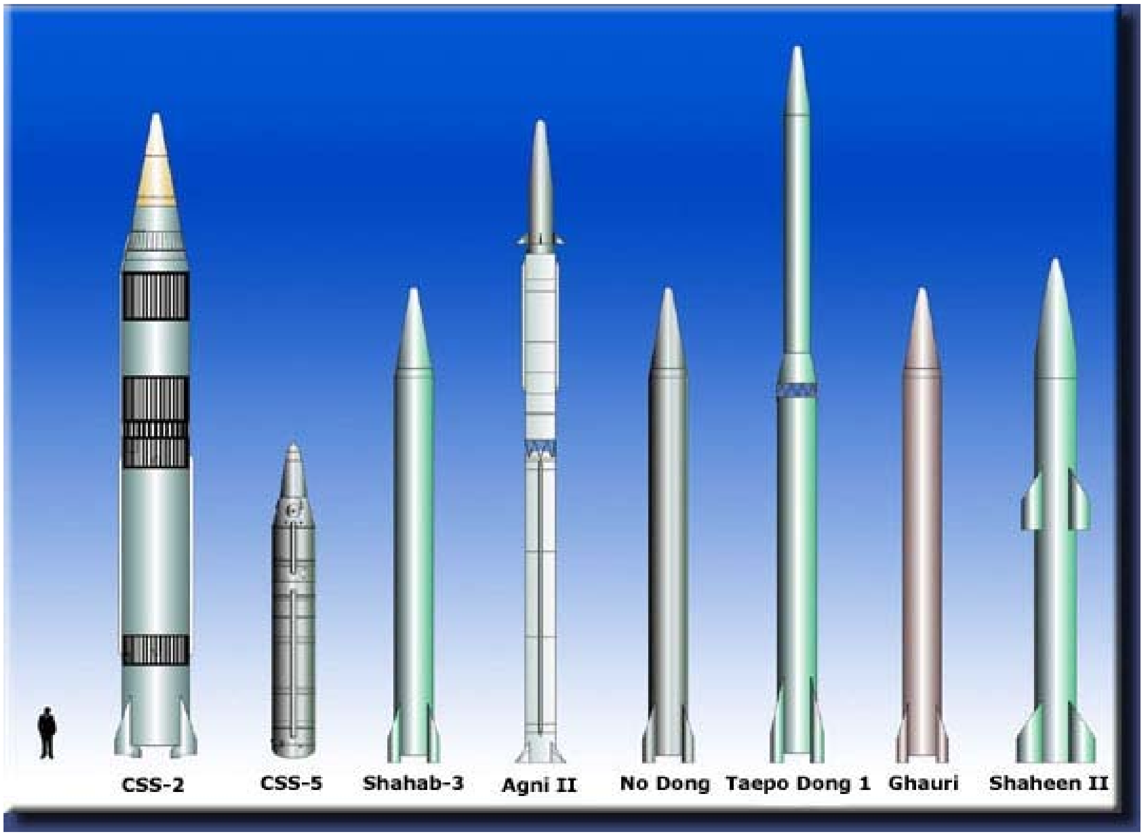
SRBM Characteristics

Missiles	Producer	Propellant	Deployment Mode	Maximum Range (miles)
SCUD B (SS-1c Mod 1)	Russia	Liquid	Road-mobile	185
SS-1c Mod 2	Russia	Liquid	Road-mobile	150+
SS-21 Mod 2	Russia	Solid	Road-mobile	43
SS-21 Mod 3	Russia	Solid	Road-mobile	75
SS-23	Russia*	Solid	Road-mobile	185+
SS-X-26	Russia	Solid	Road-mobile	185+
Iskander-E	Russia	Solid	Road-mobile	170+
CSS-6	China	Solid	Road-mobile	370
CSS-7	China	Solid	Road-mobile	185
CSS-8	China	First stage: solid Second stage: liquid	Road-mobile	93
SCUD B	North Korea	Liquid	Road-mobile	185
SCUD C	North Korea	Liquid	Road-mobile	310
Prithvi I	India	Liquid	Road-mobile	93
Prithvi II	India	Liquid	Road-mobile	155
Dhanush	India	Liquid	Ship-based	155
Hatf-1	Pakistan	Solid	Road-mobile	50
Shaheen	Pakistan	Solid	Road-mobile	280+
Vector **	Egypt	Solid	Road-mobile	425+
Al Hussein	Iraq	Liquid	Road-mobile	350+
Al Samoud	Iraq	Liquid	Road-mobile	90+

SRBM Order of Battle---Selected Countries

Country	Missile System	No. of Launchers*	Country	Missile System	No. of Launchers*
Afghanistan	SCUD B	Fewer than 50	North Korea	SCUD B	Fewer than 50
Belarus	SCUD B	Fewer than 50		SCUD C	Fewer than 50
	SS-21	Fewer than 100	Pakistan	Hatf-1	Undetermined
Bulgaria	SCUD B	Fewer than 50		CSS-7 (M-11)	Fewer than 50
	SS-23	Fewer than 50		Shaheen	Not yet deployed
China	CSS-6	Fewer than 50	Russia**	SS-1c Mod 2	Undetermined
	CSS-7	Not yet deployed		SS-21	More than 200
Egypt	SCUD B	Fewer than 50		SS-X-26	Not yet deployed
	Vector	Not yet deployed	Slovakia	SS-21	Fewer than 50
India	Prithvi	Fewer than 50		SS-23	Fewer than 50
Iran	CSS-8	Fewer than 50	Syria	SCUD B	Fewer than 50
	SCUD B	Fewer than 50		SCUD C	Fewer than 50
	SCUD C	Fewer than 50		SS-21	Fewer than 50

Country	Missile System	No. of Launchers*	Country	Missile System	No. of Launchers*
Iraq	Al Hussein	Undetermined	Turkmenistan	SCUD B	Fewer than 50
	Al Samoud	Not yet deployed	Ukraine	SCUD B	Fewer than 100
Kazakhstan	SCUD B	Fewer than 50		SS-21	Fewer than 100
	SS-21	Fewer than 50	Vietnam	SCUD B	Fewer than 50
Libya	SCUD B	Fewer than 100	Yemen	SCUD B	Fewer than 50
				SS-21	Fewer than 50



IRBM Characteristics

Missiles	Country	No. of Stages	Propellant	Deployment Mode	Maximum Range (miles)	No. of Launchers*
CSS-2	China	1	Liquid	Transportable (limited mobility)	1,750	Fewer than 50
CSS-2**	Saudi Arabia (Chinese-produced)	1	Liquid	Transportable (limited mobility)	1,500+	Fewer than 50
CSS-5 Mod 1	China	2	Solid	Road-mobile	1,100+	Fewer than 50
CSS-5 Mod 2	China	2	Solid	Road-mobile	1,100+	Fewer than 50
No Dong	North Korea	1	Liquid	Road-mobile	800	Fewer than 50
Taepo Dong 1***	North Korea	2	Liquid	Undetermined	1,250+	Not yet deployed
Agni II	India	2	Solid	Mobile	1,250+	Not yet deployed

Missiles	Country	No. of Stages	Propellant	Deployment Mode	Maximum Range (miles)	No. of Launchers*
New IRBM****	India	2	Solid	Mobile	2,000+	Not yet deployed
Ghauri	Pakistan	1	Liquid	Road-mobile	800	Not yet deployed
Shaheen II	Pakistan	2	Solid	Road-mobile	1,250+	Not yet deployed
New MRBM****	Pakistan	Undetermined	Undetermined	Undetermined	1,500+	Not yet deployed
Shahab 3	Iran	1	Liquid	Road-mobile	800	Not yet deployed
Shahab 4****	Iran	Undetermined	Liquid	Undetermined	1,200+	Not yet deployed
Shahab 5****	Iran	Undetermined	Undetermined	Undetermined	Undetermined	Not yet deployed

ICBM Characteristics

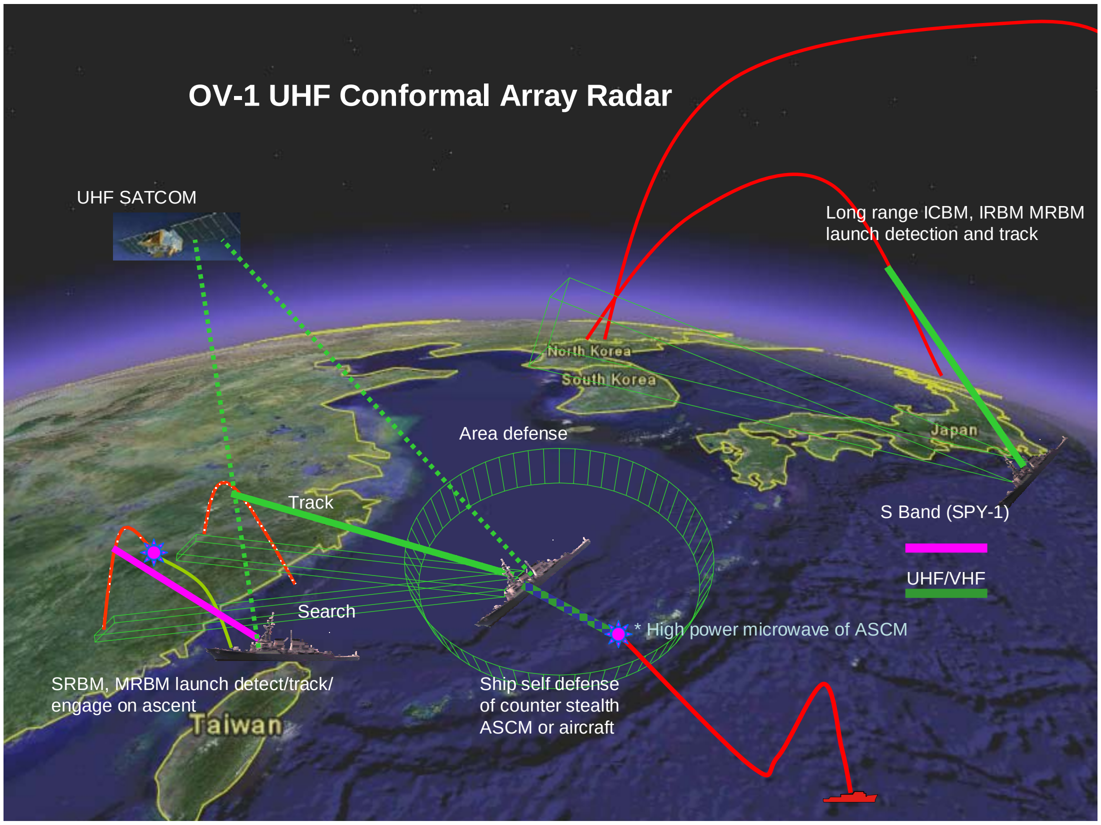
Missiles	Country	No. of Stages	Warheads per Missile	Booster Propellant	Deployment Mode	Maximum Range* (miles)	No. of Launchers

Missiles	Country	No. of Stages	Warheads per Missile	Booster Propellant	Deployment Mode	Maximum Range* (miles)	No. of Launchers
SS-18 Mod 4	Russia	2 + PBV	10	Liquid	Silo	5,500+	180 (total for Mods 4 and 5)
SS-18 Mod 5	Russia	2 + PBV	10	Liquid	Silo	6,000+	
SS-19 Mod 3	Russia	2 + PBV	6	Liquid	Silo	5,500+	150
SS-24 Mod 1	Russia	3 + PBV	10	Solid	Rail-mobile	5,500+	36
SS-24 Mod 2**	Russia	3 + PBV	10	Solid	Silo	5,500+	10
SS-25	Russia	3 + PBV	1	Solid	Road-mobile	7,000+	360
SS-27	Russia	3 + PBV	1	Solid	Silo and road-mobile	7,000+	20
New ICBM***	Russia	Undetermined	Undetermined	Solid	Silo and/or mobile	5,500+	Not yet deployed
CSS-3	China	2	1	Liquid	Silo and transportable	3,400+	Fewer than 25
CSS-4 Mod 1	China	2	1	Liquid	Silo	8,000+	About 20 (total for Mods 1 and 2)
CSS-4 Mod 2	China	2	1	Liquid	Silo	8,000+	
DF-31	China	3	1	Solid	Road-mobile	4,500+	Not yet deployed
New ICBM***	China	3	1	Solid	Mobile	7,000+	Not yet deployed
Taepo Dong 2***	North Korea	2	1	Liquid	Undetermined	3,400+	Not yet deployed

SLBM Characteristics

Missiles	Country	No. of Stages	Warheads per Missile	Booster Propellant	Submarine Class	Maximum Range (miles)	Total No. of Launch Tubes
SS-N-8	Russia	2	1	Liquid	DELTA I	5,000+	48
SS-N-18	Russia	2 + PBV	3	Liquid	DELTA III	3,500+	176
SS-N-20	Russia	3 + PBV	10	Solid	TYPHOON	5,500+	120
SS-N-23	Russia	3 + PBV	4	Liquid	DELTA IV	5,000+	112
Bulava-30*	Russia	Undetermined	Undetermined	Solid	DOLGORUKIY	5,000+	Not yet deployed
CSS-NX-3	China	2	1	Solid	XIA	1,000+	12; not yet deployed
JL-2*	China	3	1	Solid	Type 094	4,500+	Not yet deployed
Sagarika*	India	Undetermined	Undetermined	Undetermined	Undetermined	180+	Not yet deployed

Attachment 2: OV-1



Reference:

(a) Office of Naval Research (ONR) One Page Aperstructures Slide, undated

(b) Solitario, Bill, Northrop Grumman Ship Systems Integrated Topside Demonstration System presentation, undated

(c) Congressional Budget Office, Alternative for Boost-Phase Missile Design, July 2004

(d) East, Jim, Implications of a Japanese Ballistic Missile System

(e) http://www8.janes.com.libproxy.nps.navy.mil/Search/documentView.do?docId=/content1/janesdata/srep/srep085/s0850005.htm@current&pageSelected=allJanes&keyword=ss-18&backPath=http://search.janes.com/Search&Prod_Name=SREP085&#Ref4

Document Technical Note		**Document** DARBC-TN-02
Program: DARBC		**Classification:** Unclassified

TITLE: Digital Array Radar for BMD and Counter-Stealth (DARBC) Radar Cross Section Model

PROBLEM STATEMENT:

Determining target RCS data from model simulations is a critical starting point for radar system range and power calculations. This technical note deals with the Radar Cross Section (RCS) parameter of the radar range equation for the detection of ballistic missiles. This technical note provides calculations used to model a notional ballistic missile RCS. Conditions are described that should be taken into consideration when determining DARBC system requirements such as radar position relative to the target, target angular orientation to the radar system, target geometry, radar frequency or wavelength, radar frequency polarization, glint, and RCS scintillation statistical models.

Expected Outputs of study:

RCS model in excel

RCS data based on a defined assumption set

RCS Model in Matlab

Prepared by: Mark Mihocka	**Original Date:** 31 August 2006	**Comments:** Last revision submitted
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Jack Chung	**Date:** 1 Sept 2006	Final Addendum to last revision submitted
Reviewed by: Ian Barford	**Date:**	
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 1 September, 2006	Final submission of technote
Reviewed by: Robert Hazle	**Date:**	Checked problem statement
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Approved by: Professor Green	**Date:**	

I. PURPOSE

The purpose of this technical note is to propose a model to approximate the Radar Cross Section (RCS) of a notional ballistic missile threat. The following section will provide some discussion and theory involved with modeling RCSs. Finally, the model will be described and used to estimate the RCS of a ballistic missile threat to be used in the Radar Technical Parameters research for the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter Stealth (DARBC).

II. DISCUSSION

RCS DEFINITION

Electromagnetic waves with any specified polarization are normally diffracted or scattered in all directions when incident on a target.[72] Scattered waves are broken down into two parts, those waves with the same polarization as the receiving and antenna and those with different polarization as the receiving antenna, which the antenna does not respond. The two parts are orthogonal to each other and referred to as Principal Polarization (PP) and Orthogonal Polarization (OP). The intensity of the backscattered energy with the same polarization as the receiving antenna is used to define the target RCS.

When a target is illuminated by RF energy it acts like an antenna and has near and far fields. In general, waves reflected and measured in the near field are spherical. In the far field the wave fronts are decomposed into a linear combination of plane waves.[73]

Assume the power density of a wave incident on a target located at a range R away from the radar is P_D. The amount of reflected power from the target can be shown as follows.

$$P_r = \sigma P_{D_i} \qquad \text{(Equation 1)}$$

where σ denotes target cross section[74]

Define P_{D_r} as the power density of the scattered waves at the receiving antenna. The power density can be represented as

$$P_{D_r} = \frac{P_r}{4\pi R^2} \qquad \text{(Equation 2)}$$

Combining the equations

$$P_r = \sigma P_{D_i} \qquad \text{(Equation 3)}$$

$$P_{D_r} = \frac{\sigma P_{D_i}}{4\pi R^2} \qquad \text{(Equation 4)}$$

$$\sigma = 4\pi R^2 \left(\frac{P_{D_i}}{P_{D_r}} \right) \qquad \text{(Equation 5)}$$

In order to ensure the receiving antenna is in the far field (i.e. the scattered waves received by the antenna are planar) write the equation as

$$\sigma = 4\pi R^2 \lim_{R \to \infty} \left(\frac{P_{D_r}}{P_{D_i}} \right) \qquad \text{(Equation 6)}$$

This is the defining equation for monostatic RCS, backscattered RCS or what is simply known as target RCS.[75]

Backscattered RCS is measured from all waves scattered in the direction of the radar and has the same polarization as the receiving antenna. Backscattered RCS represents a portion of the total scattered RCS σ_t, shown as follows,

$$\sigma_t > \sigma \qquad \text{(Equation 7)}$$

Assuming a spherical coordinate system defined by (ρ, θ, φ) then at range ρ the target scattered cross section is a function of (θ, φ). Let the angles (θ_i, φ_i) define the direction of propagation of the incident waves. Let the angles (θ_s, φ_s) define the direction of propagation of the scattered waves. Monostatic RCS is defined as the special case when $\theta_s = \theta_i$ and $\varphi_s = \varphi_i$.

The bistatic RCS is the RCS measured by the radar at angles $\theta_s \neq \theta_i$ and $\varphi_s \neq \varphi_i$.[76] The total target scattered RCS is given by the equation

$$\sigma_t = \frac{1}{4\pi}\int_{\phi_i=0}^{2\pi}\int_{\theta_s=0}^{\pi}\sigma(\theta_s, \varphi_s)\sin\theta_s d\theta d\varphi_s \qquad \text{(Equation 8)}$$

The amount of backscattered waves from a target is proportional to the ratio of the target extent (size) to the wavelength, λ, of the incident waves.

$$c = \lambda f \qquad \text{(Equation 9)}$$

$$\lambda = \frac{c}{f} \qquad \text{(Equation 10)}$$

where c represents the speed of light, f represents frequency and λ represents wavelength

A radar will not be able to detect targets much smaller than its operating wavelength.

The frequency region where the target extent and the wavelength are comparable is referred to as the *Rayleigh* region. The frequency region where the target extent is much larger than the radar operating wavelength is referred to as the *optic* region. Typically, the majority of radar applications fall within the optical region.

The analysis presented here assumes far field monostatic RCS measurements in the optic region. The RCS analysis presented here is mainly concerned with *narrow band* cases (i.e. extent of the target under consideration falls within a single range bin of the radar).

RCS DEPENDENCY ON ASPECT ANGLE AND FREQUENCY

RCS fluctuates as a function of radar aspect angle and frequency. For this analysis, isotropic scatterers shall be considered (i.e. ones that scatter incident waves equally in all directions). For example, consider the geometry in the following figure. Consider two unity (i.e. one square meter) isotropic scatterers with spacing of one meter are aligned and placed along the radar sight (i.e. zero aspect angle) at a far field range *R*.

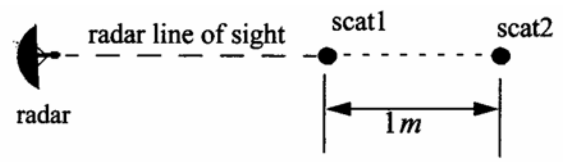

Figure 1. RCS Dependency on Aspect Angle [77]

To compute the composite RCS of the two scatterers measured by the radar as the aspect angle is changed from 0 to 180 degrees the following analysis is used. The composite RCS consists of the superposition of the two individual RCSs. The composite RCS is dependent upon the phase that corresponds to the electrical spacing between the two scatterers. For a zero degree aspect angle, the composite RCS is two square meters.

If the scatterer (scat1) closest to the radar in the previous figure is the phase reference, when the aspect angle is varied, the composite RCS changes by the phase corresponding to the electrical spacing between the two scatterers. The electrical spacing between the two scatterers can be represented by the following equation.[78]

$$\frac{2\times\left(d\times\cos\theta\right)}{\lambda} \qquad \text{(Equation 11)}$$

d is the physical distance between scatterers in meters
θ is the aspect angle in degrees
λ is the radar operating wavelength

RCS is dependent on radar aspect angle; thus, knowledge of the constructive and destructive interference between the individual scatterers can be very critical when a radar tries to extract the RCS of maneuvering targets.[79] RCS is dependent on the radar aspect angle for two reasons: (1) the aspect angle may be continuously changing and (2) complex target RCS can be viewed to be made up from contributions of many individual scattering points (often referred to as scattering centers) distributed on the target surface.

Many approximate RCS prediction methods generate a set of scattering centers that define the backscattering characteristics of such complex targets. Small frequency changes can cause large RCS fluctuations when the scatterer spacing is large. More variation in frequency is required to produce significant RCS fluctuation when scattering centers are relatively close.

RCS DEPENDENCY ON POLARIZATION

In most radar simulations it is desirable to obtain the complex-valued electric field scattered by the target at the radar. In such cases it is useful to use a quantity called the normalized electric field. Assume the incident electric field has a magnitude of unity and the phase of the field is centered at a point at the target, typically, the center of gravity.[80]

The incident electric field can be written as

$$E_i = e^{jk\left(\vec{r_i} \cdot \vec{r}\right)} \qquad \text{(Equation 12)}$$

where $\vec{r_i}$ is the direction of incidence with respect to the phase center

$\vec{r}$ is a location at the target with respect to the phase center

The normalized scattered field is given by the following equation.

$$E_s = \sigma E_i \qquad \text{(Equation 13)}$$

The quantity E_s is independent of radar and target location. It may be combined with an incident magnitude and phase.[81]

Polarization

The x and y electric field components for a wave traveling along the positive z direction are given by the following equations.

$$E_x = E_1 \sin(\omega t - kz) \qquad \text{(Equation 14)}$$

$$E_y = E_2 \sin(\omega t - kz + \delta) \qquad \text{(Equation 15)}$$

where $k = 2\pi / \lambda$

$\omega =$ wave frequency

$\delta =$ time phase angle at which E_y leads E_x

$E_1 =$ wave amplitude in x-direction

$E_2 =$ wave amplitude in y-direction

When two or more electromagnetic waves combine, their electric fields are integrated vectorially at each point in space for any specified time. In general the combined vector traces an ellipse when observed in the x-y plane, as illustrated in the following figure.[82]

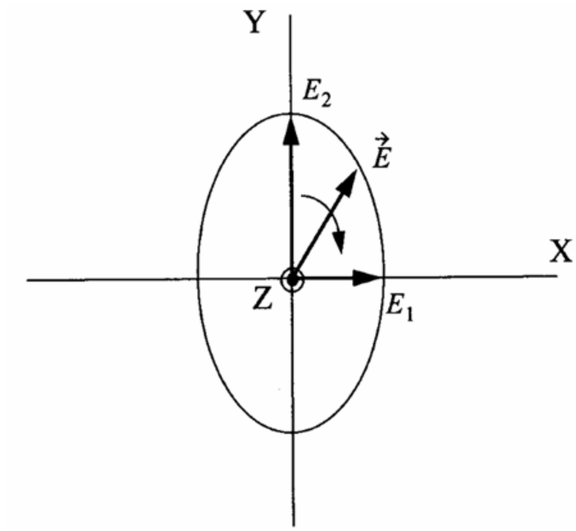

Figure 2. Ellipse Traced by Combined Vector[83]

The ratio of the major to the minor axes of the polarization ellipse is called the axial ratio (abbreviated as AR). When the AR is unity, the polarization ellipse becomes a circle and the corresponding wave is referred to as circularly polarized. When the wave amplitude along the x-direction is zero and AR approaches infinity (i.e. very large) the wave is referred to as linearly polarized.

Combining the two previous equations gives the instantaneous total electric field.

$$\vec{E} = E_x + E_y \qquad \text{(Equation 16)}$$

$$= \hat{a}_x E_1 \sin(\omega t - kz) + \hat{a}_y E_2 \sin(\omega t - kz + \delta) \qquad \text{(Equation 17)}$$

where $\hat{a}_x =$ unit vector in the x-direction
$\hat{a}_y =$ unit vector in the y-direction

at z = 0

$$E_x = E_1 \sin(\omega t) \qquad \text{(Equation 18)}$$

$$E_y = E_2 \sin(\omega t + \delta) \qquad \text{(Equation 19)}$$

Substituting $\sin(\omega t)$ with the ratio $\frac{E_x}{E_1}$ and using trigonometric properties, the equation becomes the following.

$$\vec{E} = E_x + E_y \qquad \text{(Equation 20)}$$

$$= E_1 + E_2 \sin(\omega t + \delta) \qquad \text{(Equation 21)}$$

$$= E_1 + E_2[\sin(\omega t)\cos(\delta) + \cos(\omega t)\sin(\delta)] \qquad \text{(Equation 22)}$$

$$= E_1 + E_2[\frac{E_x}{E_1}\cos(\delta) + \cos(\omega t)\sin(\delta)] \qquad \text{(Equation 23)}$$

$$= E_1 + \frac{E_2 E_x}{E_1}\cos(\delta) + E_2\cos(\omega t)\sin(\delta) \qquad \text{(Equation 24)}$$

$$\frac{E_x^2}{E_1^2} - \frac{2E_x E_y\cos(\delta)}{E_1 E_2} + \frac{E_y^2}{E_2^2} = (\sin(\delta))^2 \qquad \text{(Equation 25)}$$

For z=0, observe that the above equation for the instantaneous total electric field is independent of ωt.

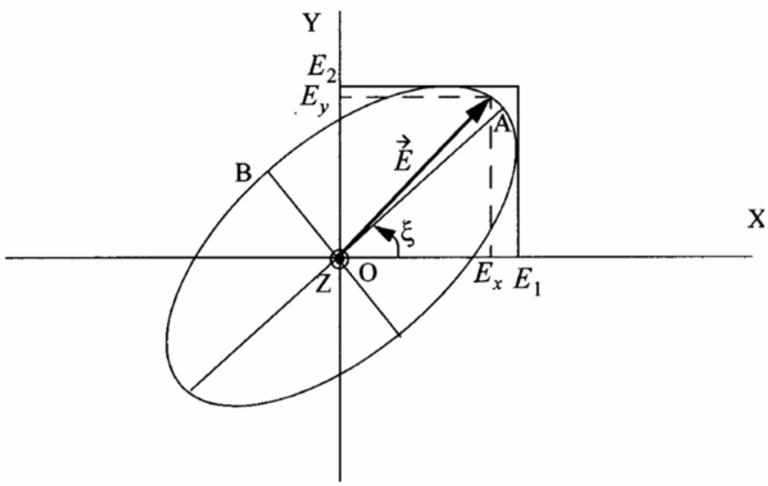

Figure 3. A General Case of the Polarization Ellipse[84]

The previous figure illustrates the most general case of the polarization ellipse. The tilt angle of the ellipse is defined as angle ξ. The tilt angle is the angle between the major axis of the polarization ellipse and the positive x-axis.

When $E_1 = 0$, the wave is said to be linearly polarized in the y-direction (more commonly known as vertical polarization). When $E_2 = 0$, the wave is said to be linearly polarized in the x-direction (more commonly known as horizontal polarization). Linear polarization also occurs at a tilt angle (ξ) of 45°, when $E_1 = E_2$. When $E_1 = E_2$ and the tilt angle equals 90°, the wave is said to be left circularly polarized (LCP). When $E_1 = E_2$ and the tilt angle equals negative 90°, the wave is said to be right circularly polarized (RCP).

In general, an arbitrarily polarized electric field may be written as the sum of two circularly polarized fields. For an arbitrarily polarized electric field,

$$\vec{E} = \vec{E}_R + \vec{E}_L \qquad \text{(Equation 26)}$$

where $\vec{E}_R$ is the RCP field and
$\vec{E}_L$ is the LCP field.

The RCP field can be written as

$$\vec{E}_R = \vec{E}_V + j\vec{E}_H \qquad \text{(Equation 27)}$$

and the LCP field can be written as

$$\vec{E}_L = \vec{E}_V - j\vec{E}_H \qquad \text{(Equation 28)}$$

where $\vec{E}_V$ and $\vec{E}_H$ are the fields with vertical and horizontal polarizations, respectively.

Combining the equations for the RCP and LCP fields yields the following.

$$E_R = \frac{E_H - jE_V}{\sqrt{2}} \qquad \text{(Equation 29)}$$

$$E_L = \frac{E_H - jE_V}{\sqrt{2}} \qquad \text{(Equation 30)}$$

Using matrix notation the RCP and LCP fields and the vertical and horizontal polarization fields can be written as follows.

$$\begin{bmatrix} E_R \\ E_L \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix} \begin{bmatrix} E_H \\ E_V \end{bmatrix} = [T] \begin{bmatrix} E_H \\ E_V \end{bmatrix} \qquad \text{(Equation 31)}$$

$$\begin{bmatrix} E_H \\ E_V \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} \begin{bmatrix} E_R \\ E_L \end{bmatrix} = [T]^{-1} \begin{bmatrix} E_H \\ E_V \end{bmatrix} \qquad \text{(Equation 32)}$$

$[T]$ is the transformation matrix

For many targets the scattered waves will have different polarization than the incident waves. This phenomenon is known as depolarization or cross-polarization. Perfect reflectors reflect waves in such a way that an incident wave with horizontal polarization remains horizontal and an incident wave with vertical polarization remains vertical but are phase shifted 180°. An incident wave that is RCP becomes LCP when reflected and a wave that is LCP becomes RCP after reflection from a perfect reflector. When a radar

transmits LCP waves the receiving antenna needs to be RCP in order to receive the principal polarization (PP) RCS and LCP to receive the orthogonal polarization (OP).

RCS OF SIMPLE OBJECTS

Electromagnetic wave scattering from simple objects has historically received a great amount of attention as analytical expressions since the scattered fields can often be derived. The RCS of complex targets can be computed in many cases by using the RCS of simple shapes. The most common procedure is to break the target into component parts and to combine them vectorially.[85]

The study of simple objects is of great value as they tend to provide insight into the important scattering mechanisms inherent to wave interactions with real world objects. The expressions presented in this analysis represent an approximation to the radar cross section of the object when it is large compared to the wavelength, known as the "high frequency" or "optical" scattering regime. These expressions are derived from analytical expressions using asymptotic limits for wavelength or empirical fits to simplify their evaluation.[86] Computational methods can also be used in the "low frequency" or "resonance" regime to calculate the RCS.

The perfectly conducting sphere is considered as the simplest target to examine. For this case, the complexity of the exact solution is overwhelming when compared to the optical region approximation.[87] The formulas used in this analysis are typically physical optics (PO) approximations for the backscattered RCS measured by a far field radar in the direction (θ, φ) as illustrated in the following figure. For the formulas used in this analysis, the radar is illuminating an object from the positive z-direction.[88]

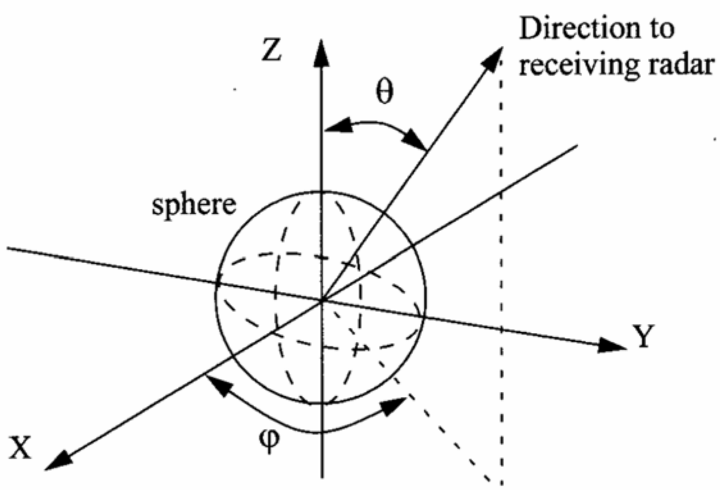

Figure 4. Direction of Radar Receiving Backscattered Waves[89]

Circular Flat Plate

Since the plate has circular symmetry the backscattered RCS has no dependency on φ, see the following figure.[90] The circular flat plate backscattered RCS is only aspect angle (θ) dependent. For normal incidence (i.e. $\theta = 0$), the backscattered RCS for a circular flat plate can be represented by the following equation.

$$\sigma = \frac{4\pi^3 r^4}{\lambda^2} \qquad \text{(Equation 33)}$$

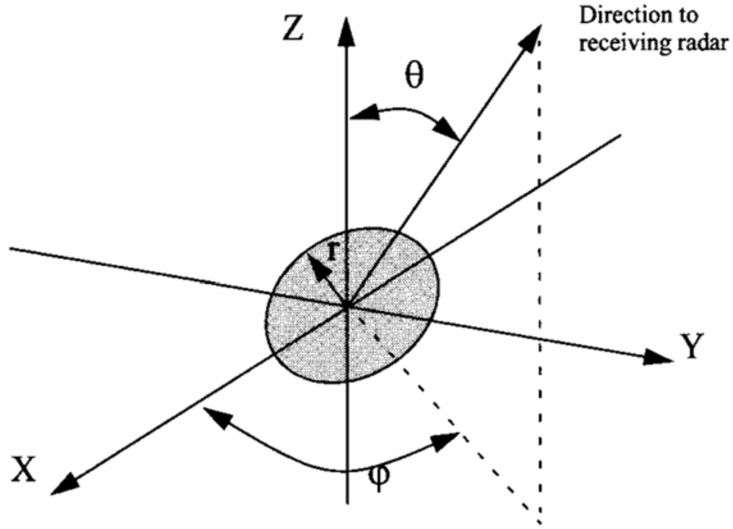

Figure 5. Circular Flat Plate[91]

For normal incidence, the backscattered RCS for any linearly polarized incident waves can be approximated by either of the following equations.[92]

$$\sigma = \frac{\lambda r}{8\pi \sin\theta (\tan(\theta))^2} \qquad \text{(Equation 34)}$$

$$\sigma = \pi k^2 r^4 \left(\frac{2J_1(2kr\sin\theta)}{2kr\sin\theta}\right)^2 (\cos\theta)^2 \qquad \text{(Equation 35)}$$

where $k = \frac{2\pi}{\lambda}$ and

$J_1(\beta)$ is the first order spherical Bessel function evaluated at β

Rectangular Flat Plate

Consider a perfectly conducting rectangular thin plate in the x-y plane as shown in Figure 6.[93]

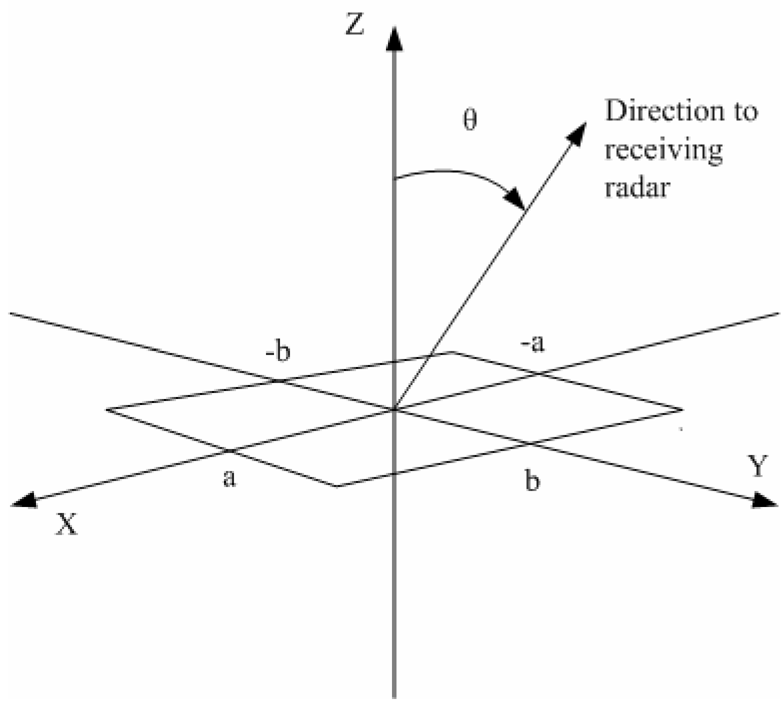

Figure 6. Rectangular Flat Plate

The two sides are denoted by *2a* and *2b*.[94] For a linearly polarized incident wave in the x-z plane, the horizontal and vertical backscattered RCS are, respectively, given by[95]

$$\sigma_V = \frac{b^2}{\pi}\left|\sigma_{1V} - \sigma_{2V}\left[\frac{1}{\cos\theta} + \frac{\sigma_{2V}}{4}\left(\sigma_{3V} + \sigma_{4V}\right)\right]\sigma_{5V}^{-1}\right|^2 \qquad \text{(Equation 36)}$$

$$\sigma_H = \frac{b^2}{\pi}\left|\sigma_{1H} - \sigma_{2H}\left[\frac{1}{\cos\theta} - \frac{\sigma_{2H}}{4}\left(\sigma_{3H} + \sigma_{4H}\right)\right]\sigma_{5H}^{-1}\right|^2 \qquad \text{(Equation 37)}$$

where $k = 2\pi/\lambda$

$$\sigma_{1V} = \cos(k\sin\theta) - j\left(\frac{\sin(ka\sin\theta)}{\sin\theta}\right) = (\sigma_{1H})^* \qquad \text{(Equation 38)}$$

$$\sigma_{2V} = \frac{e^{j\left(ka - \pi/4\right)}}{\sqrt{2\pi}\,(ka)^{3/2}} \qquad \text{(Equation 39)}$$

$$\sigma_{3V} = \frac{(1+\sin\theta)e^{-jka\sin\theta}}{(1-\sin\theta)^2} \quad \text{(Equation 40)}$$

$$\sigma_{4V} = \frac{(1-\sin\theta)e^{jka\sin\theta}}{(1+\sin\theta)^2} \quad \text{(Equation 41)}$$

$$\sigma_{5V} = 1 - \frac{e^{j\left(2ka-\pi/2\right)}}{8\pi(ka)^3} \quad \text{(Equation 42)}$$

$$\sigma_{2H} = \frac{4e^{j\left(ka+\pi/4\right)}}{\sqrt{2\pi}(ka)^{1/2}} \quad \text{(Equation 43)}$$

$$\sigma_{3H} = \frac{e^{-jka\sin\theta}}{1-\sin\theta} \quad \text{(Equation 44)}$$

$$\sigma_{4H} = \frac{e^{jka\sin\theta}}{1+\sin\theta} \quad \text{(Equation 45)}$$

$$\sigma_{5H} = 1 - \frac{e^{j\left((2ka+\pi/2\right)}}{2\pi(ka)} \quad \text{(Equation 46)}$$

Equations 36 and 37 are valid and quite accurate for aspect angles $0^\circ \le \theta \le 80^\circ$.[96] For aspect angles near 90°, empirical expressions for the RCS are given by the following equations[97]

$$\sigma_H \to 0 \quad \text{(Equation 47)}$$

$$\sigma_V = \frac{ab^2}{\lambda}\left\{\left[1+\frac{\pi}{2\left(2a/\lambda\right)^2}\right]+\left[1-\frac{\pi}{2\left(2a/\lambda\right)^2}\right]\cos\left(2ka-\frac{3\pi}{5}\right)\right\} \quad \text{(Equation 48)}$$

The backscattered RCS for a perfectly conducting thin rectangular plate for incident waves at any θ, φ can be approximated by[98]

$$\sigma = \frac{4\pi a^2 b^2}{\lambda^2}\left(\frac{\sin(ak\sin\theta\cos\varphi)}{ak\sin\theta\cos\varphi}\frac{\sin(bk\sin\theta\sin\varphi)}{bk\sin\theta\sin\varphi}\right)^2(\cos\theta)^2 \quad \text{(Equation 49)}$$

Equation 49 is independent of the polarization, and is only valid for aspect angles $\theta \leq 20^{\circ}$.[99]

The equation used for Tables 4 and 5 below is as follows and gives a maximum approximation of the maximum backscatter RCS of a perfectly conducting thin rectangular plate for comparison with the cylindrical data.

$$\sigma = \frac{4\pi a^2 b^2}{\lambda^2} \qquad \text{(Equation 50)}$$

Cylinder

The normal and non-normal incidence backscattered RCS due to a linearly polarized incident wave for a finite length right cylinder (see Figure 7) are given by the following equations.[100]

$$\sigma_{\theta_n} = \frac{2\pi H^2 r}{\lambda} \qquad \text{(Equation 51)}$$

$$\sigma = \frac{\lambda r \sin\theta}{8\pi(\cos\theta)^2} \qquad \text{(Equation 52)}$$

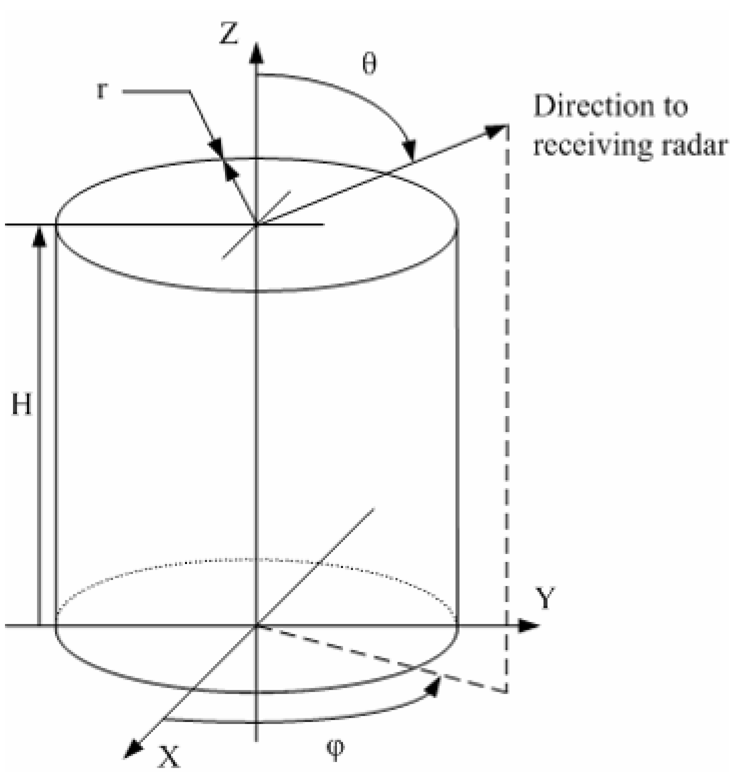

Figure 7. Circular Right Cylinder

GLINT

Typically there is relative motion between the radar and observed target. This implies the observed RCS measured by the radar fluctuates over time as a function of frequency and target aspect angle. This observed RCS is referred to as the dynamic cross section or dynamic RCS.[101]

The dynamic RCS may fluctuate in amplitude or phase or both simultaneously. Phase fluctuation is called glint. Amplitude fluctuation is called scintillation.[102] Glint causes the target far field backscattered waveforms to be non-planar. Glint affects radar performance in applications where high precision and accuracy are required due to introduction of linear errors in radar measurements. These applications include missile seekers, precision instrumentation tracking systems and automated aircraft landing systems.[103] RCS scintillation variations are dependent on target size, shape, dynamics and relative motion to the radar antenna. Due to the variety of sources of RCS scintillation, RCS changes are modeled statistically as random processes.[104]

RCS SCINTILLATION STATISTICAL MODELS

The most commonly used RCS scintillation statistical models are the chi-square and Swerling cases. Selection of a model depends on the nature of the target to be modeled.

Chi-Square

The chi-square distribution of degree 2 is applicable to a number of targets. The probability density function (pdf) is given by the following equation. As the degree becomes larger the distribution corresponds to a smaller range of values (i.e. approaches a static RCS with no dynamic behavior).[105]

$$f(\sigma) = \frac{m}{\Gamma(m)\sigma_{av}} \left(\frac{m\sigma}{\sigma_{av}} \right)^{m-1} e^{-m\sigma / \sigma_{av}} \qquad \text{for } \sigma \geq 0 \qquad \text{(Equation 53)}$$

where $\Gamma(m) =$ gamma function with argument m

$\sigma_{av} =$ RCS overall target fluctuation

Swerling I and II

Swerling I and II fluctuations correspond to a chi-square of degree 2 distribution. Swerling I RCS samples are correlated throughout an entire scan but uncorrelated scan to scan. Swerling I is a characteristic of slowly fluctuating RCS samples. Swerling II fluctuations are faster than Swerling I but the samples are uncorrelated pulse to pulse. Swerling I and II cases apply to targets consisting of many independent fluctuating point

scatterers of approximately equal physical dimensions. These targets can be represented as a number of independently fluctuating reflectors of about equal echoing area.[106] The pdf for Swerling cases I and II is given by the following equation.[107]

$$f(\sigma) = \frac{1}{\sigma_{av}} \exp\left(-\frac{\sigma}{\sigma_{av}}\right) \qquad \text{for } \sigma \geq 0 \qquad \text{(Equation 54)}$$

Swerling III and IV

Swerling III and IV fluctuations correspond to chi-square of degree 4 distribution. Swerling cases III and IV are applicable to targets that can be represented by one dominant scatterer and many other small reflectors.[108] These targets can be represented as one large reflector together with a number of small reflectors or as one large reflector subject to small changes in orientation.[109] Swerling III fluctuations are similar to Swerling I and Swerling IV fluctuations are similar to Swerling II. The pdf of Swerling III and IV cases is given by the following equation.[110]

$$f(\sigma) = \frac{4\sigma}{\sigma_{av}^2} \exp\left(-\frac{2\sigma}{\sigma_{av}}\right) \qquad \text{for } \sigma \geq 0 \qquad \text{(Equation 55)}$$

III. MODEL DESCRIPTION

The Excel model uses Equations 51 and 52 to determine the normal and non-normal backscatter RCS for a right cylinder. From Table 1, the inputs to the model are the cylinder radius and height, in meters, DARBC frequency, in megahertz, and roll viewing angle, in degrees. The model outputs

Symbol	Description	Units	Status
r	*radius*	*meters*	*input*
h	*height*	*meters*	*input*
f	*frequency*	*MHz*	*input*
θ	*roll viewing angle*	*degrees*	*input*
σ	*nonnormal backscatter RCS*	*dBsm*	*output*
σ_n	*normal backscatter RCS*	*dBsm*	*output*

Table 1. Model Inputs and Outputs

are the non-normal and normal backscatter RCS in decibels referenced to one square meter. Figure 8 shows a screenshot of the model.

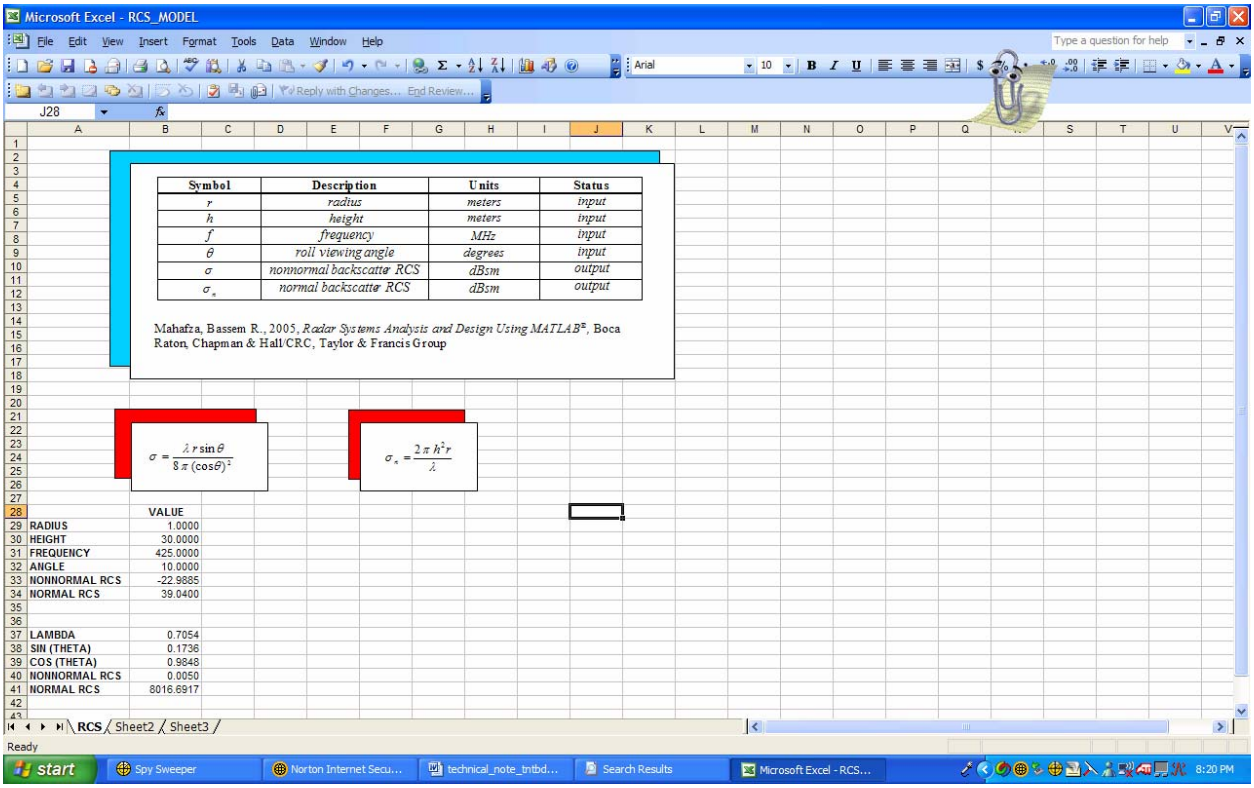

Figure 8. Screenshot of Model in Microsoft Excel

A second model using Matlab simulation analysis software was used to generate mathematical algorithms to calculate the RCS for circular cylinder shape to simulate the ballistic missile target. The normal and non-normal incidence backscattered RCS equations (51) and (52) for a finite length right cylinder were used. Apply the radius and height values for the normal broadside 90 degree backscatter RCS calculation and calculation of radius value with non-normal aspect angle backscatter calculation to get a RCS value in meter square. The calculated RCS value is then converted to dbsm and plotted against aspect angle. VHF, UHF, and S-band frequencies were plotted to compare the different RCS resolution to determine the range of aspect angle required to in order to maintain 10 meter square or greater target resolution.

IV. MODEL RESULTS

Defined Assumption Set for Excel model

a. DARBC System bandwidths: 216-225 MHz & 420-450MHz
b. Initial assumption of 10 square meters for threat RCS in the S-band
c. Roll viewing angle will be 90° for RCS calculations
d. DARBC system detection range will be 1,500 kilometers

e. Threat will be detected during boost stage

f. Ignore non-normal RCS backscatter

f (MHz)	216	225	420	450
λ (m)	1.3889	1.3333	0.7143	0.6667
λ (in)	54.6807	52.4934	28.1215	26.2467

Table 2. Wavelengths of DARBC System Bandwidth Limits

Description

For the BM RCS analysis presented here, the non-normal RCS value will be ignored. From assumptions 4 and 5, the roll viewing angle will not change for this analysis. The roll viewing angle is another name for the aspect angle. The threat will be in its boost stage 180 to 320 seconds after launch (see DARBC CONOPS). Another consideration due to the range and angle assumptions will be a rectangular flat plate RCS.

Frequency (MHz)	216	220	225	420	435	450
Normal RCS (dbsm)	35.76	35.84	35.94	38.65	38.81	38.95

Table 3. Model Output for a Threat Similar to Taep'o-dong 2

For example, use a cylinder length of 35 meters and diameter of 1.36 meter. These dimensions are similar to North Korea's Taep'o-dong 2 missile. The model results for the normal backscatter RCS are shown in Table 3. The results vary from approximately 36 to 39 dBsm, which equates to 3900 to 7900 square meters. Data on several missile threats has been tabulated with rectangular flat plate and cylinder normal backscatter RCS data in the following tables.

Threat Length (m)	Threat Diameter (m)	Flat Plate RCS @ 220 MHz (sqm)	Flat Plate RCS @ 435 MHz (sqm)	Flat Plate RCS @ 3.3 GHz (sqm)	Cylinder RCS @ 220 MHz (sqm)	Cylinder RCS @ 435 MHz (sqm)	Cylinder RCS @ 3.3 GHz (sqm)
6.4	.65	119.2	466.1	26,313.8	61.3	121.4	1,840.1
35.0	2.1	36,507.9	142,731.8	8,214,307.0	5,930.8	11,726.8	177,798.9
35.0	1.36	15,311.8	59,863.2	3,445,166.0	3,840.9	7,594.5	115,145.9
16.2	1.36	3,270.8	12,787.7	738,081.1	822.9	1,627.0	24,668.5

Threat Length (m)	Threat Diameter (m)	Flat Plate RCS @ 220 MHz (sqm)	Flat Plate RCS @ 435 MHz (sqm)	Flat Plate RCS @ 3.3 GHz (sqm)	Cylinder RCS @ 220 MHz (sqm)	Cylinder RCS @ 435 MHz (sqm)	Cylinder RCS @ 3.3 GHz (sqm)
27.0	0.88	3,827.9	14,965.8	858,398.8	1,479.0	2,924.4	44,338.8
27.0	1.36	9,102.1	35,585.9	2,050,225.3	2,285.7	4,519.5	68,523.6
32.0	0.88	5,374.2	21,010.9	1,205,761.9	2,077.5	4,107.8	62,281.1
32.0	1.36	12,787.6	49,994.8	2,879,877.6	3,210.7	6,348.4	96,252.6
36.0	3.35	98,289.3	384,273.6	22,115,199.7	10,009.4	19,791.2	300,070.6
13.0	2.25	5,801.6	22,682.0	1,300,912.2	876.6	1,733.4	26,281.1
18.4	2.25	11,582.8	45,284.2	2,606,135.1	1,756.2	3,472.5	52,649.2
25	2	16,894.8	66,052.0	3,801,336.0	2,881.8	5,698.1	86,394.0

Table 4. RCS Data in Square Meters for Several Unnamed Threats

Threat Length (m)	Threat Diameter (m)	Flat Plate RCS @ 220 MHz (dBsm)	Flat Plate RCS @ 435 MHz (dBsm)	Flat Plate RCS @ 3.3 GHz (dBsm)	Cylinder RCS @ 220 MHz (dBsm)	Cylinder RCS @ 435 MHz (dBsm)	Cylinder RCS @ 3.3 GHz (dBsm)
6.4	.65	20.7	26.6	44.2	17.9	20.8	32.7
35.0	2.1	45.6	51.5	69.2	37.7	40.7	52.5
35.0	1.36	41.9	47.8	65.4	35.8	38.8	50.6
16.2	1.36	35.2	41.1	58.7	29.2	32.1	43.9
27.0	0.88	35.8	41.7	59.3	31.7	34.7	46.5
27.0	1.36	39.6	45.5	63.1	33.6	36.5	48.4
32.0	0.88	37.3	43.2	60.8	33.2	36.1	47.9
32.0	1.36	41.1	47.0	64.6	35.1	38.0	49.8
36.0	3.35	49.9	55.8	73.5	40.0	43.0	54.8
13.0	2.25	37.6	43.5	61.1	29.4	32.3	44.2
18.4	2.25	40.6	46.6	64.2	32.4	35.4	47.2
25	2	42.3	48.2	65.8	34.6	37.6	49.4

Table 5. RCS Data in Decibels for Several Unnamed Threats

Defined Assumption Set for Matlab model

1. DARBC System bandwidths: 216-225 MHz & 420-450MHz
2. Initial assumption of 10 square meters for threat RCS in the S-band
3. **All aspect angles including** 90° **will be for RCS calculations**
4. Threat will be detected during boost stage so a near-normal RCS should be used
5. Non-normal RCS backscatter will not ignored
6. Using normalized target value of 2 meters for radius and 18 meters for height to simulate a ballistic target

Description

Using normalized target value of 2 meters for radius and 18 meters for height to simulate a ballistic target for normal broadside 90 degree backscatter RCS calculation, equation 51 and non-normal aspect angle backscatter RCS calculation, equation 52. The following figures describe the results of the Matlab analysis using VHF (225 MHz), UHF (425 MHz), and S-Band (3.3 GHz):

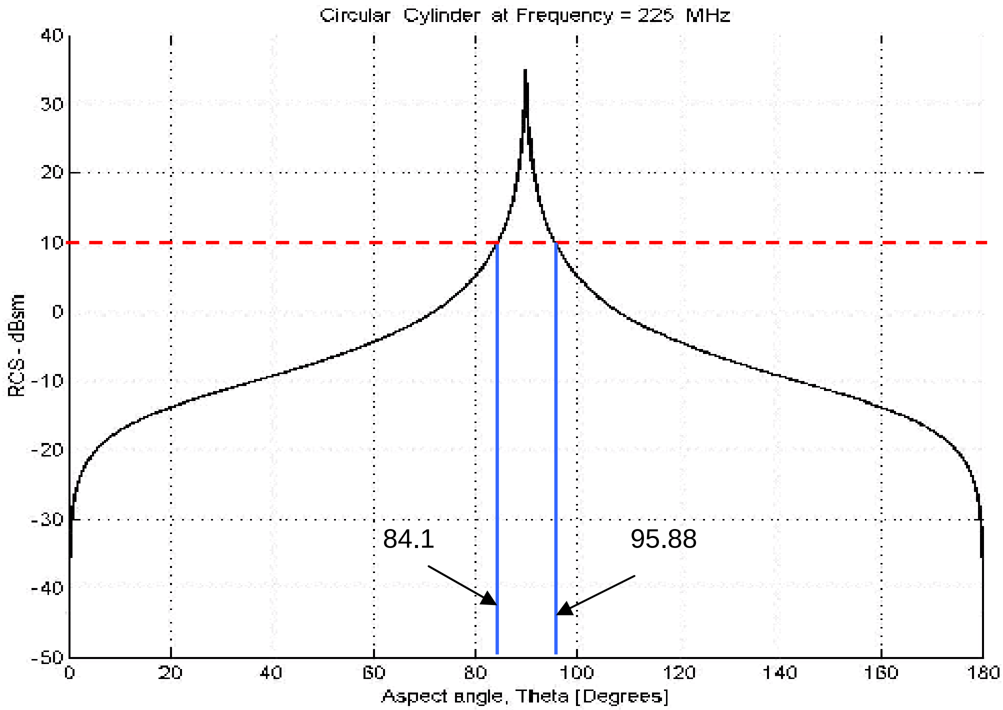

Figure 9. Matlab model output for 225 MHz

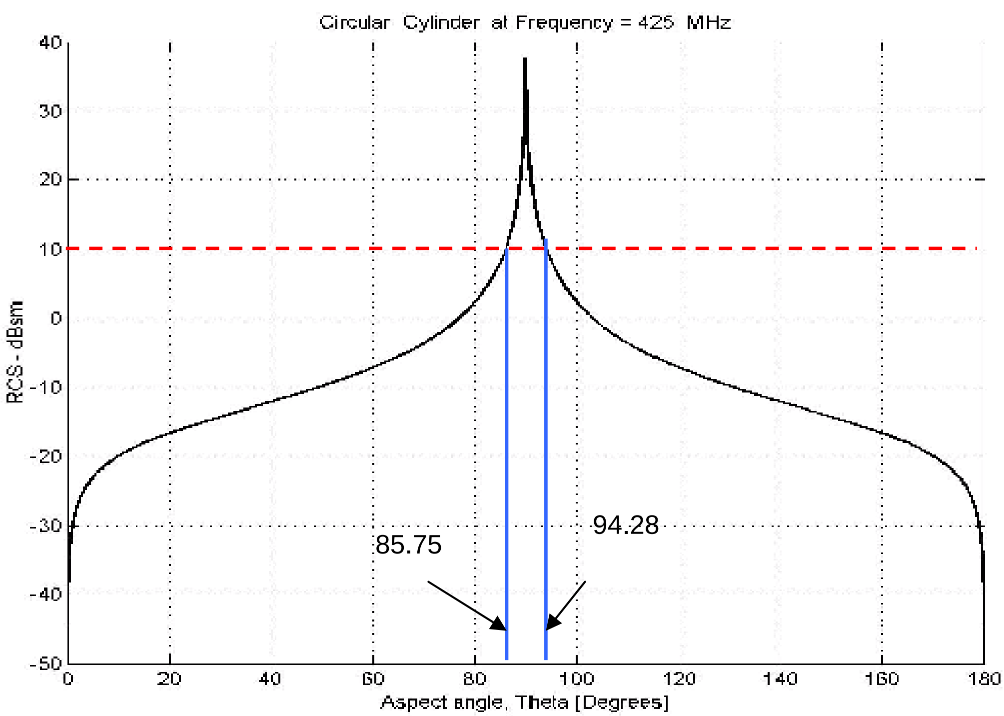

Figure 10. Matlab model output for 425 MHz

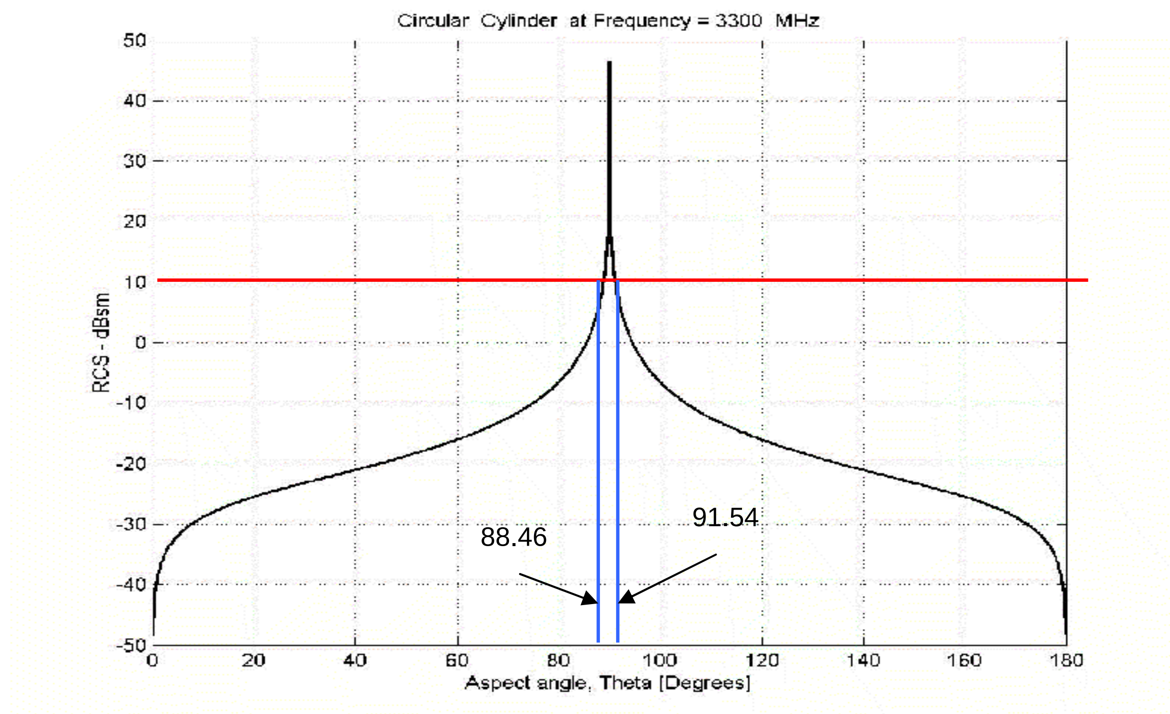

Figure 11. Matlab model for 3.3 GHz

Figures 9, 10, and 11 shown that for DARBC radar to maintain RCS resolution of 10 dbsm or greater it must at least retain aspect angle range between 84.1 and 95.88 degrees for VHF, 85.75 and 94.28 degrees for UHF radar when compared with 88.46 and 91.54 degrees for S-band Radar. From the above equations the range of aspect angle dependent on the wavelength. The lower the frequency, the larger is the wavelength. Therefore, the simulation had shown that DARBC radar provides wider angular resolution range (11.78 degrees for VHF and 8.53 degrees for UHF) due to its use of lower frequency versus 3.08 degrees for S-band Radar for retaining minimum of 10 dbsm RCS resolution [39].

V. CONCLUSION

This TECHNOTE has presented a brief background to RCS theory. An attempt has been made to describe the effect that radar aspect angle, target geometry, radar frequency, polarization and RCS fluctuation has on RCS measurement. To build a better model, more information is required about the scattering center set of the threat. Although a missile threat is considered between a simple and complex shape, the RCS can vary substantially. Observing the results in Tables 4 and 5, the calculated RCS data for a

rectangular flat plate and right cylinder shows how much the data can vary without taking into account aspect or azimuth angle. To accurately develop probability of detection curves for the DARBC system, statistical modeling of the RCS is required. The statistical model selection is dependent on more knowledge of the range of missile threats.

The RCS analysis shows a range of calculated normal RCS values from 119.2 to 384,273.6 square meters in the DARBC system proposed bandwidths. From this analysis, the following should be considered. An initial assumption was made to use a threat RCS of 10 square meters for DARBC system calculations. The lowest calculated value is only one order of magnitude higher than the initial assumption. The output data from the model supports the initial assumption of using an RCS of 10 square meters. Designing the DARBC system to detect a launch of a 10 square meter target within the proposed bandwidths with a high probability of detection will make this radar an effective part of a ballistic missile defense system.

Complementing the Excel model, Matlab analysis output shown in figure 1, 2, and 3 uses the assumption that a fixed near-normal aspect angle of 88.4° is based on the anticipated ballistic missile flight path characteristics of 10 meter square RCS in S-band relative to the DARBC ship. This notional ballistic missile had an equivalent RCS of $77m^2$ in the UHF band and $146m^2$ in the VHF band. These values aided in determining both operational and technical requirements for the DARBC.

VI. BIBLIOGRAPHY

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DARBC-TN-03 SEARCH PATTERN OPTIONS

Document Technical Note		**Document** DARBC-TN-03
Program: DARBC		**Classification:** Unclassified

TITLE: Radar Search Patterns for the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter stealth (DARBC)

PROBLEM STATEMENT:

A study on search pattern options for the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-Stealth (DARBC) system is needed in order to define and optimize how the radar will effectively search for enemy Ballistic Missiles (BMs) and other air threats. The optimal search pattern(s) used by the DARBC can be derived from the Operational Requirements for the radar system which define the missions of the system. Based on the specific information on the threats, different search patterns and their combinations can be compared for their effectiveness. Based on the technical capabilities of the radar, multiple search patterns may be able to be used at once. This study should define the different types of search patterns available.

Expected Outputs of study:

The optimal combination of radar search patterns that will allow the DARBC to most effectively meet its operational objectives.

Prepared by: Carla Bacchus	**Original Date:** 21 July 2006	**Comments:** Submission of Rev 1 of the document.
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Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 1 September 2006	Final submission of this technote.
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

The purpose of this technote is to define and articulate the radar search pattern for the DARBC. The technical information provided by this analysis will assist Team R in other analysis including the Probability of Detection (P_D) calculations. Tradeoff studies can be done between the technical requirements and the physical limitations which will aid in choosing the most viable solution for the radar search pattern requirement that is required for the DARBC system.

II. BACKGROUND

[1]In order to describe where a target is located, its range (distance) and angle (direction) are required. The radar range to target is defined as R = c/2 * t where c is the speed of light and t is the round trip propagation time. The angle is broken down into a horizontal component (azimuth) and a vertical component (elevation). They are measured by determining the antenna's pointing angles at the time signal detection is made, on the presumption that signals detected always originate from the direction of the antenna's beam at the time of detection.

[2]Radars can differentiate between targets in various directions as well as detect targets at greater ranges. The radar's antenna concentrates the radiated energy into a narrow beam. To find a target, the beam is systematically swept through the region in which targets are expected to appear. The beam's path is known as the search scan pattern. The region covered by the scan is called the scan volume or frame and the length of time the beam takes to scan the complete frame is called the frame time. We will explore some search scan patterns and determine which one will be best suited for our purpose.

III. DISCUSSION

[3] Radar systems are often identified by the type of SCANNING used. Scanning is the systematic movement of a radar beam in a definite pattern while searching for or tracking a target. The type and method of scanning used depends on the radar. In some cases, the type of scan will change with the particular system mode of operation. For example the search mode scan may be quite different from that of the track mode scan. The two basic methods of beam scanning are MECHANICAL and ELECTRONIC. In mechanical scanning, the beam can be moved in various ways: (1) The entire antenna can be moved in the desired pattern; (2) the energy feed source can be moved relative to a fixed reflector; or (3) the reflector can be moved relative to a fixed source. In electronic scanning, the beam is effectively moved by such means as (1) switching between a set of feeder sources, (2) varying the phasing between elements in a multi-element array, or (3) comparing the amplitude and phase differences between signals received by a multi-element array. A combination of mechanical and electronic scanning is also used in some antenna systems. Since the DARBC will be a digital phased array radar, it will be steered electronically.

Electronic scanning can accomplish lobe motion more rapidly than, and without the inherent maintenance disadvantages of, the mechanical systems. Because electronic scanning cannot generally cover as large an area of space, it is sometimes combined with mechanical scanning in particular applications. Since the DARBC will have the majority of its elements on the port and starboard sides of the ship, it may be necessary to orient the ship so that one side of the array is facing the desired area to scan. This will allow the maximum swing of the beam to be used to cover the largest amount of area where the threat is expected to come from.

With MONOPULSE (SIMULTANEOUS) LOBING, all range, bearing, and elevation-angle information of a target is obtained from a single pulse. Monopulse scanning is used in fire-control tracking radars.

For target tracking, the radar discussed here produces a narrow circular beam of pulsed-rf energy at a high pulse-repetition rate. Each pulse is divided into four signals which are equal both in amplitude and phase. These four signals are radiated at the same time from each of four feed-horns that are grouped in a cluster. The resulting radiated energy is focused into a beam by a lens. Energy reflected from targets is refocused by the lens back into the feed-horns. The total amount of the energy received by each horn varies, depending on the position of the target relative to the beam axis. This is illustrated in figure 2 for four targets at different positions with respect to the beam axis. Note that a phase inversion takes place at the microwave lens similar to the image inversion that takes place in an optical system.

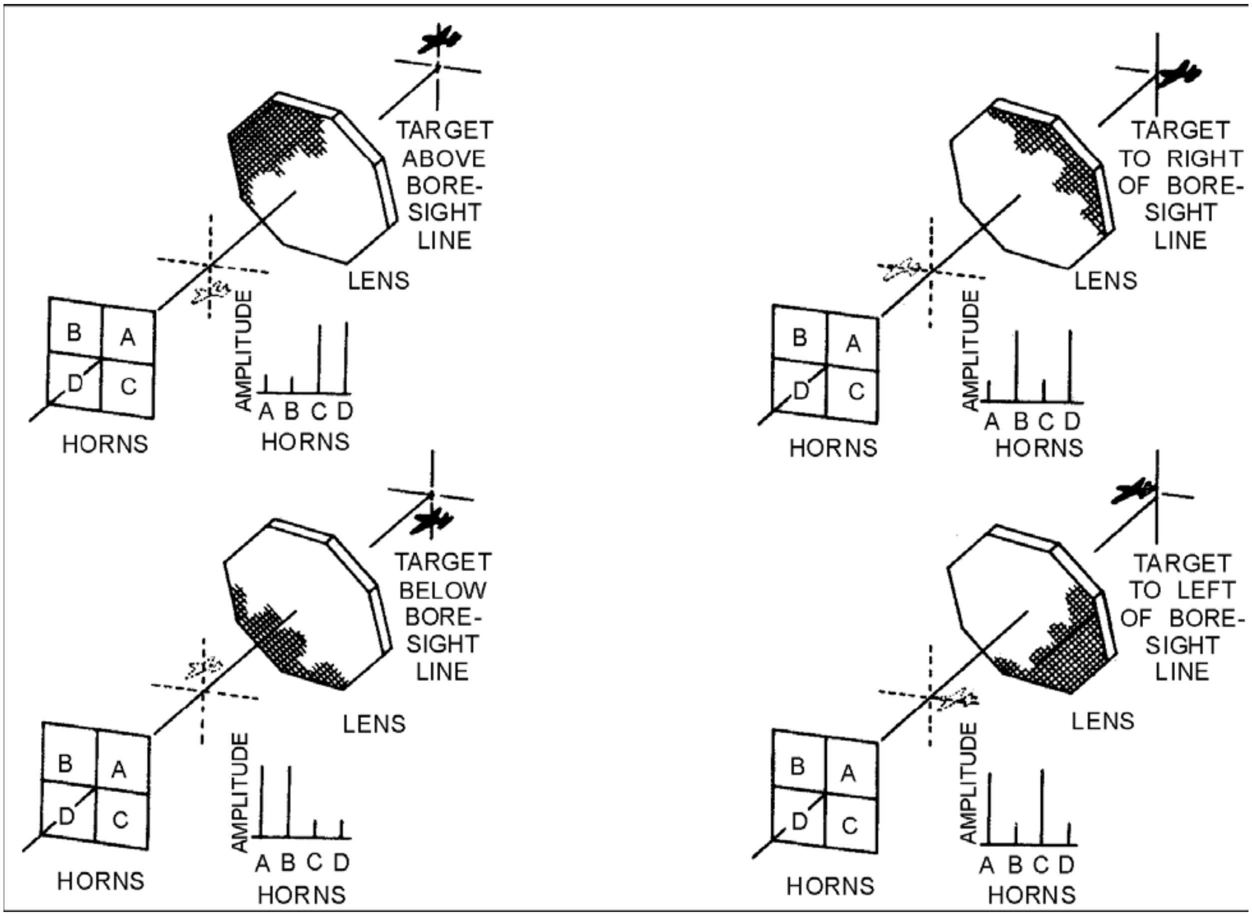


Figure 2- Monopulse Scanning

The amplitude of returned signals received by each horn is continuously compared with those received in the other horns. Error signals are generated which indicate the relative position of the target with respect to the axis of the beam. Angle servo circuits receive these error signals and correct the position of the radar beam to keep the beam axis on target.

The TRAVERSE (BEARING) SIGNAL is made up of signals from horn **A** added to **C** and from horn **B** added to **D**. By waveguide design, the sum of **B** and **D** is made 180 degrees out of phase with the sum of **A** and **C**. These two are combined and the traverse signal is the difference of (**A** + **C**) - (**B** + **D**).

Since the horns are positioned as shown in figure 2, the relative amplitudes of the horn signals give an indication of the magnitude of the traverse error. The elevation signal consists of the signals from horns **C** and **D** added 180 degrees out of phase with horns **A** and **B** [(**A** + **B**) - (**C** + **D**)]. The sum, or range, signal is composed of signals from all four feed-horns added together in phase. It provides a reference from which target direction from the center of the beam axis is measured. The range signal is also used as a phase reference for the traverse and elevation-error signals.

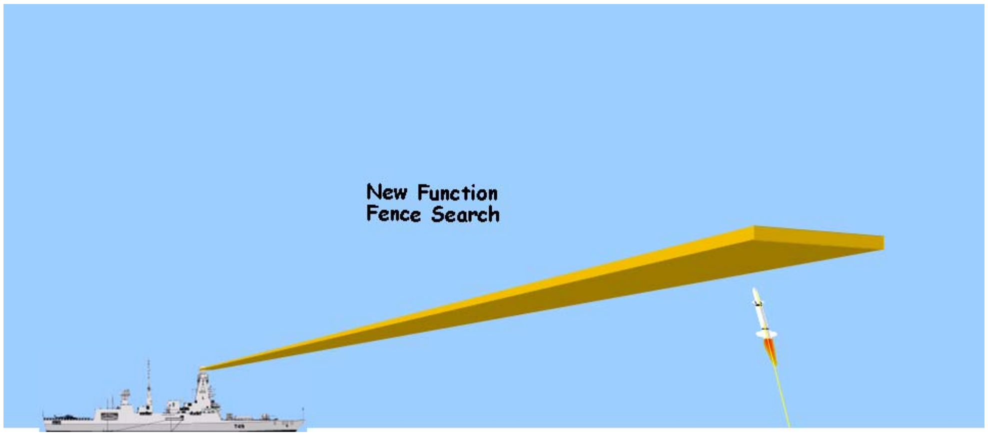
The traverse and elevation error signals are compared in the radar receiver with the range or reference signal. The output of the receiver may be either positive or

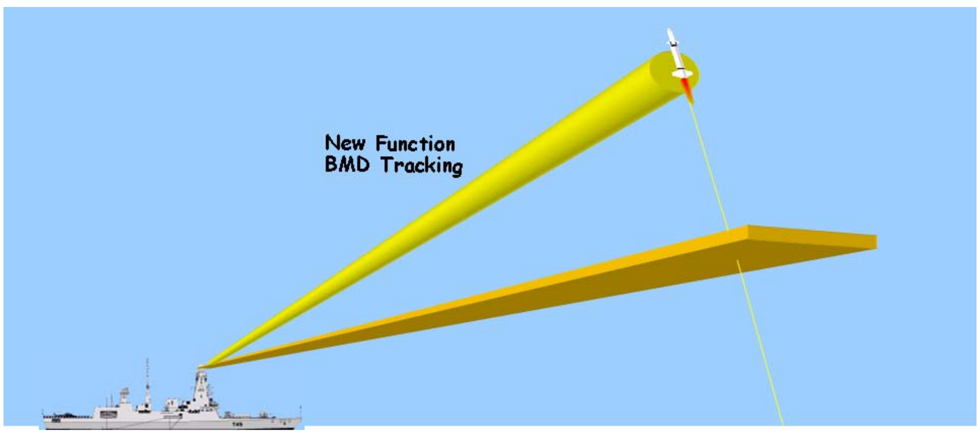
negative pulses; the amplitudes of the pulses are proportional to the angle between the beam axis and a line drawn to the target. The polarities of the output pulses indicate whether the target is above or below, to the right or to the left of the beam axis. Of course, if the target is directly on the line of sight, the output of the receiver is zero and no angle-tracking error is produced.

An important advantage of monopulse-tracking radar over mechanically steered radars is that the instantaneous angular measurements are not subject to errors caused by target SCINTILLATION. Scintillation can occur as the target maneuvers or moves and the radar pulses bounce off different areas of the target. This causes random reflectivity and may lead to tracking errors. Monopulse tracking radar is not subject to this type of error because each pulse provides an angular measurement without regard to the rest of the pulse train; no such cross-section fluctuations can affect the measurement. An additional advantage of monopulse tracking is that no mechanical action is required.[3]

[4]The U.S. military operates an extensive early warning network consisting of ground-based radars and space-based sensors in order to detect Inter-Continental Ballistic Missile (ICBM) and sea-launched ballistic missile (SLBM) raids against the United States and Canada. Part of this early warning network includes two PAVE PAWS (Phased-Array Warning System) sites at Beale Air Force Base (AFB), California, and Cape Cod Air Force Station (AFS), Massachusetts, and one Ballistic Missile Early Warning System (BMEWS) site at Clear AFS, Alaska. Each of these sites use the same type of radar system, a Solid-State Phased-Array Radar System or SSPARS, to accomplish the missions of missile warning and space surveillance.

To detect and determine attack characteristics of ICBMs and SLBMs aimed at the United States and Canada, the radar devotes approximately one-half of its time generating what is called a “surveillance fence.” This constitutes the center of the main beam scanning at elevations between 3 and 10 degrees above horizontal over a 240-degree (120 degrees per face) scan area. The surveillance fence is normally at 3 degrees. In the surveillance mode, the direction of the beam is steered according to a computer-programmed pattern, moving from one position to another in tens of microseconds. In the surveillance mode, both faces of the radar are simultaneously active, sending out two parallel beams moving in a fashion similar to windshield wipers. Under normal operational circumstances, the radar is transmitting 11 percent of the time to maintain the surveillance fence and waiting/receiving the return signal 89 percent of the time. The SSPARS is capable of transmitting for up to 18 percent of the time to perform the surveillance mission with no space surveillance mission. The diagrams below demonstrate the Fence Search Scan/Pattern as well as how the fence search could cue tracking of a target which breaks the plane of the fence.





A volume search is a 360° search pattern that covers all area around the sensor out to a defined range. This volume search is best used in the Air Defense (AD) role where all areas of the sky should be monitored. This type of search is effective against multiple kinds of threats as long as the threat is within the volume being covered and is detectable by the radar (i.e. has a large enough Radar Cross Section (RCS) and is not to fast for the sensor). The downside of the volume search is that it requires a lot of the radar's resources to cover the full volume, taking a relatively large amount of time to complete the search pattern compared to the fence search. Also, in order to reduce the time required to complete the search, the radar detection range is reduced in order to decrease the volume. This has an impact on long range performance which is needed for the BMD mission.

A sector search is similar to a volume search except range, bearing, and elevation windows are defined, effectively creating a volume search on a limited and defined area. The sector search can be defined in the area where hostile threats are expected to originate reducing the resources required as compared to using a volume search. With the extra available resources, it would be possible to perform one or several sector searches while also performing a fence search.

IV. CONCLUSION

[5]Successful detection is a precondition for setting the entire BMD system in motion. The problem with detection is that a huge volume of space has to be covered to enable a reliable surveillance, and this entails the implementation of special search techniques.

The DARBC is a phased-array radar performing a search for ballistic missiles primarily. That being said, a combination of a fence search along with a sector or volume search pattern should be used depending on the operational scenario. In fence-surveillance one or more rows of radar beams create narrow-elevation "fences" which in azimuth extend the full width of the desired surveillance sector. Every ascending missile has to cross these fences and thus be detected. However, this technique is radar-energy intensive. Sector-surveillance concentrates a sufficient number of radar beams to cover a smaller volume of space, in azimuth, elevation and range. The choice to use one or both techniques will be made by tactical and other policy decisions.[5]

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DARBC-TN-04 RADAR TECHNICAL PARAMETERS

Document Type: Technical Note		**Document Number:** DARBC-TN-04
Program: DARBC		**Classification:** Unclassified

TITLE: DARBC Technical Parameters Analysis

PROBLEM STATEMENT: The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) has a Key Performance Parameter (KPP) described in the DARCB Capabilities Development Document (CDD) to be able to detect a target with a Radar Cross Section (RCS) of $10m^2$ at the calculated handoff range to a notional S-Band radar with a Probability of Detection (P_D) of 0.90.[111] This notional handoff range needs to be calculated for this KPP. In order for the DARBC to meet this requirement, the characteristics of the radar need to be tuned properly. A tradeoff study between the various parameters of the radar equation for the DARBC system is needed in order to properly design the radar to meet its objectives. With these parameters defined, parametric analysis is needed to characterize the radar's ability to detect different sized targets (in RCS) at different ranges.

Expected Outputs of Study:

1. Analysis of DARCB radar equation including description and tradeoff study of all parameters defining values (or range of values) for those parameters so that the DARCB will be capable of meeting its operational requirements.
2. Calculated handoff range where the DARBC will cue a notional S-band radar for engagement purposes.
3. Parametric analysis of the Probability of Detection as a function of Range for various RCSs for the DARCB.

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Reviewed by: David Bedford	**Date:**	
Reviewed by: Bob Hazle	**Date:** 20 August 2006	Review
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

The purpose of this Technote is to describe and define the radar parameters of the DARBC so that the radar system will be capable of meeting the operational requirements for the system. Once the parameters are defined, analysis will be done in an effort to characterize the radar's ability to detect different types of targets. This study will also calculate the notional handoff range from the DARBC to a notional S-band radar for engagement purposes.

II. BACKGROUND

Radar systems like the DARBC can be technically described by the Radar Equation. The Radar Equation is made up of parameters which represent characteristics of the radar, the target, and the operational environment. The parameters can be optimized for maximum operational performance using the equation. The optimized values for these parameters will be the technical requirements for the system so that it will be capable of achieving the KPPs specified in the CDD.

Equation 1 is the Radar Equation solved for Signal to Noise Ratio (S/N). Note that in this equation, S/N is a dimensionless value, not in dB.

$$1)\quad \frac{S}{N} = \frac{P_t G A_e \sigma n E_i(n)}{(4\pi)^2 k_b T_o B_n F_n R_{\max}{}^4}$$

Equation 2 is the relationship between S/N and the Probabilities of Detection (P_D) and False Alarm (P_{FA}). In this relationship, S/N is in dB.

$$2)\quad \frac{S}{N} = \frac{(\log_{10} P_{FA} - \log_{10} P_D)}{\log_{10} P_D}$$

Equations 1 & 2 can be combined to form Equation 3. This equation is the base of the radar parameters analysis, allowing for the radar parameters to be adjusted so that the detection probability can be graphed as a function of range.

$$3)\quad \frac{(\log_{10} P_{FA} - \log_{10} P_D)}{\log_{10} P_D} = \frac{S}{N} = 10 * \log_{10}\left(\frac{P_t G A_e \sigma n E_i(n)}{(4\pi)^2 k_b T_o B_n F_n R_{\max}{}^4}\right)$$

III. DISCUSSION

A. APPROACH

The overall approach for the analysis was to first look at the way in which the DARBC would be used in operation. Current S-band radars used by the US Navy to search for ballistic missiles use up a lot of resources in search mode and are actually capable of tracking targets at ranges greater than their maximum search range. The DARBC will provide a benefit to current S-band radar systems by extending the search capability to detect ballistic missiles and cueing the S-band systems to track the target at a range that would have been outside the search range for the S-band radar alone.

Analysis using Equation 3 was first planned for a notional S-band radar to form a baseline needed to determine at what maximum range the current radar will be able to accurately track a ballistic missile if cued by the DARBC. A P_D vs. Range plot should be generated for the S-Band radar with parametric cures on the graph for different Radar Cross Sections (RCSs). Since the predicted RCS for a notional ballistic missile is $10m^2$ in the S-band frequency band (assuming an aspect angle of 88.46°) equaling to $77m^2$ in the UHF band and $146m^2$ in the VHF band at the same aspect angle[112], the generated plot can be analyzed to see at what range the S-band radar would have a P_D of 0.5 for this RCS. This range will be the desired track handoff range from the DARBC to the S-Band radar.

Following the analysis on the S-Band radar, the same analysis should be generated to analyze the capabilities of the DARBC. The approach said that the DARBC should be capable of tracking the notional ballistic missile with a P_D of 0.90 at the handoff range to the S-Band radar. The Range / P_D combination will drive one of the Key Performance Parameters (KPPs) for the DARBC system. The radar parameters for the DARBC should be tuned so that this goal can be met and that the parameters used are feasible.

B. CALCULATIONS

The values for the parameters listed in Equation 3 for the DARBC were derived using this equation and other equations to be described in this section. Analysis and calculations described in this section were conducted using Waterloo Maple 7 Computer Algebra System (CAS). Initially, notional values were used as the radar equations were set up in the Maple code. After the completion of the Maple code, the values of the various parameters were researched, manipulated and analyzed for their affect on the overall P_D as well as their feasibility.

Equation 4 calculates the wavelength (λ) for a given frequency. Calculations were done using one VHF (216 MHz) and one UHF (420 MHz) frequency for the DARBC. For the notional S-band radar, a frequency of 3 GHz was used. In this equation, C is the speed of light.

$$4)\quad \lambda = \frac{C}{f}$$

Equation 5 is the equation used to calculate the Antenna Effective Aperture (A_e). A typical value of 0.7 will be used for Effective Aperture Efficiency η.[113] Analysis on the array element density being conducted concurrently with this analysis shows that there are can be up to 2 elements / m^2 on the DARBC aperstructure.[114] With this specified density, A_e can be calculated based on the number of elements within the aperstructure which contribute to a single beam (n) multiplied by the efficiency η. Based on a notional hull for a new construction ship, it was found that 3411 elements can be placed one side of the ship. For this research, 3411 was used for n but sensitivity analysis will be conducted which relates P_D to n.

$$5)\quad A_e = n \times \eta$$

Equation 6 is how Gain (G) is calculated based on the Antenna Effective Aperture (A_e) and λ.

$$6)\quad G = \frac{A_e 4\pi}{\lambda^2}$$

Doppler Shift (f_D) occurs when the target being tracked is non-stationary. The echo returning to the radar receiver will be higher or lower in frequency than the transmission wave depending on if the target is closing or moving away from the radar (See Figure 1). Using the predicted velocity for a ballistic missile, f_D was calculated. Based on this f_D value, receiver noise bandwidth (B_N) was calculated to be double the value of f_D so that the DARBC would be able to track targets coming towards or going away from the radar. Calculations for B_N for the UHF and VHF frequencies are shown below. These values were used as inputs to the Maple program.

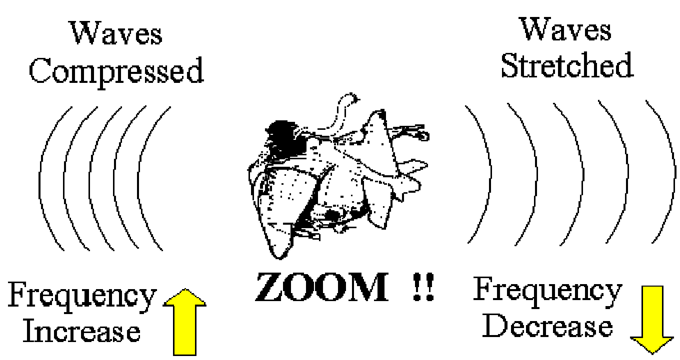


Figure 1 – Illustration of the Doppler Shift Effect

Doppler Shift and B_n[115]

Rules of Thumb for two-way signal travel
(divide in half for one-way ESM signal measurements)
At 10 GHz, f_D =
35 Hz per Knot
19 Hz per km/Hr
67 Hz per m/sec
61 Hz per yd/sec
20 Hz per ft/sec
To estimate f_D at other frequencies, multiply these by:

$$\left[\frac{f_{Xmt}\ \text{(GHz)}}{10} \right]$$

Ballistic Missile travels at 7.5 km/s = 27000 km/hr

a. $f_{D(VHF)} = \frac{19Hz}{1} \times \frac{0.216GHz}{10} = 0.4104Hz$ per $\frac{km}{hr} \times \frac{27000km}{hr} = 11.08kHz$

   i. $B_{n(VHF)} \geq 2 \times f_{D(UHF)}$ = $\mathbf{23\textit{kHz}}$

b. $f_{D(UHF)} = \frac{19Hz}{1} \times \frac{0.420GHz}{10} = 0.798Hz$ per $\frac{km}{hr} \times \frac{27000km}{hr} = 21.55kHz$

   i. $B_{n(UHF)} \geq 2 \times f_{D(VHF)}$ = $\mathbf{44\textit{kHz}}$

Based on the Maple calculations and parameter sensitivity analysis, the following parameters were used for the DARBC and S-band radar calculations (Table 1). The values listed for the DARBC in this table are the recommended values for the DARBC technical parameters (Expected Output #1).

Parameter	Description	Value Used	Maple Name
P_{max}[116]	Transmitted power [W]	500 kW (VHF, UHF), 4 MW (S-band)	P (VHF & UHF), P2 (S-band)
σ[117]	Radar cross section of target [m^2]	146 (VHF), 100, 77 (UHF), 10, 1, 0.1 [m^2]	H1V (146), H1 (100), H1U (77), H2 (10), H3 (1), H4 (0.1)
n	Number of pulses integrated	1	N
$E_i(n)$	Integration efficiency	1	E
k_B	Boltzmann's constant [J/degree K]	1.3806503E-23 J/ K	K
T_0	Standard temperature [degrees K]	290 degrees K	T
B_n	Receiver noise bandwidth	23 kHz (VHF), 44 kHz	B1 (VHF), B2

	[Hz]	(UHF), 4 MHz (S-band)	(UHF), B3 (S-band)
F_n [118]	Receiver noise figure	$1\times10^{3/5}$ = 6 dB	F
P_{FA}	Probability of False Alarm	0.01	fa
f [119]	Radar Transmit Frequency	216 MHz (VHF), 420 MHz (UHF), 3 GHz (S-band)	f1 (VHF), f2 (UHF), f3 (S-band)
η [120]	Effective Aperture Efficiency	0.7	Ef
n [121]	Number of Array Elements contributing to 1 beam	3411	n
λ	Wavelength [m]	1.3879 (VHF), 0.7138 (UHF), 0.0999 (S-band)	WL1 (VHF), WL2 (UHF), WL3 (S-band)
A_e	Antenna effective aperture [m^2]	This is a function of n and η; 1193.85 (VHF & UHF), 17.5 (S-band)	A1 (UHF), A2 (VHF), A3 (S-Band)
G	Antenna gain	This is a function of A_e and λ; 38.9 dB (VHF), 44.7 dB (UHF), 43.4 dB (S-band)	G1 (VHF), G2 (UHF), G3 (S-band)
S/N	Signal-to-noise ratio (SNR) required for detection based on a single pulse	Not directly calculated. This is a function of R_{max}.	S1 (VHF), S2 (UHF), S3 (S-band)
R_{max}	Maximum radar range or detection range [m]	Variable (see plot)	R
P_D	Probability of Detection	Variable (see plot)	D

Table 1 – Parameter values used in the Maple analysis

Based on these values above, the "Handoff Range" where the DARBC will cue the S-band radar to track a ballistic missile target will be at a range of 748 km. This is the range where the S-band radar has a P_D of 0.5 for an RCS of 10 m^2 (See Figure 2). Ignore the vertical lines on these plots as they are generated by Maple where the values go to zero.

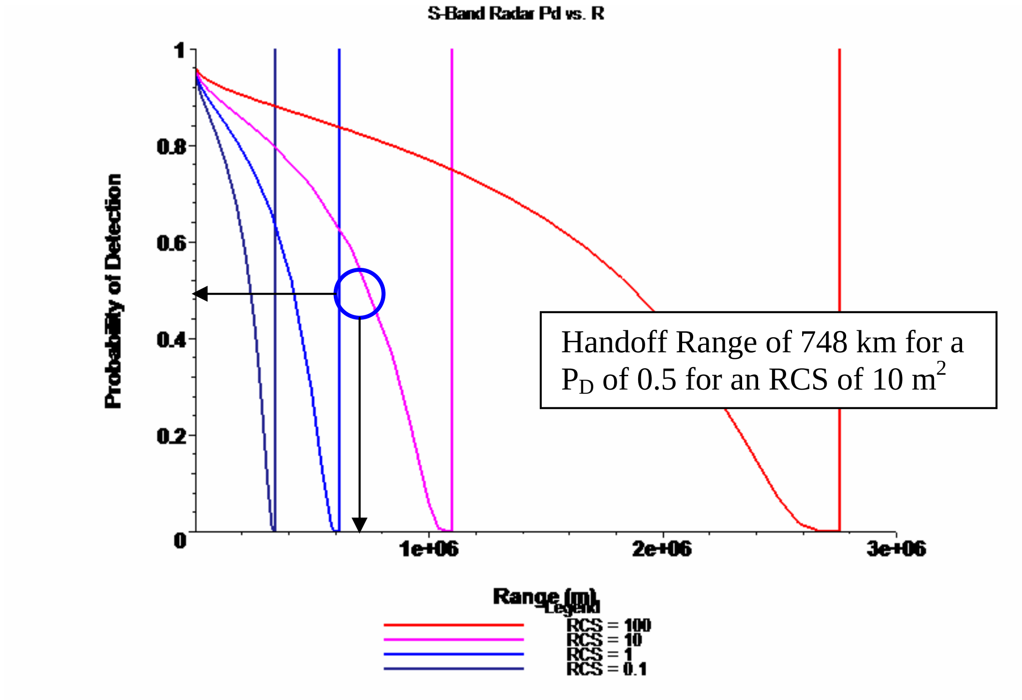


Figure 2 – Calculated Handoff Range to S-Band radar

The DARBC should have a 0.90 P_D at this range of 748 km vs. a similar ballistic missile target (RCS of 146m^2 for VHF and 77m^2 for UHF). Using the parameters in Table 1, the Maple model shows that the DARBC is able to obtain 0.906 ≈ 0.91 using both VHF and UHF spectrums. The graphs below show the anticipated performance of the DARBC using the parameters from Table 1. See Figures 3 and 4 for the P_D vs. Range parametric plots for both the VHF and UHF frequencies for the DARBC.

```
> VHFPsubD:=evalf(eval(P4VHF,R1=748000),5);#VHF Pd at handoff range vs.
Ballistic Missile (146m^2 RCS)
```

$$VHFPsubD := .90616$$

```
> UHFPsubD:=evalf(eval(P4UHF,R2=748000),5);#UHF Pd at handoff range vs.
Ballistic Missile (77m^2 RCS)
```

$$UHFPsubD := .90651$$

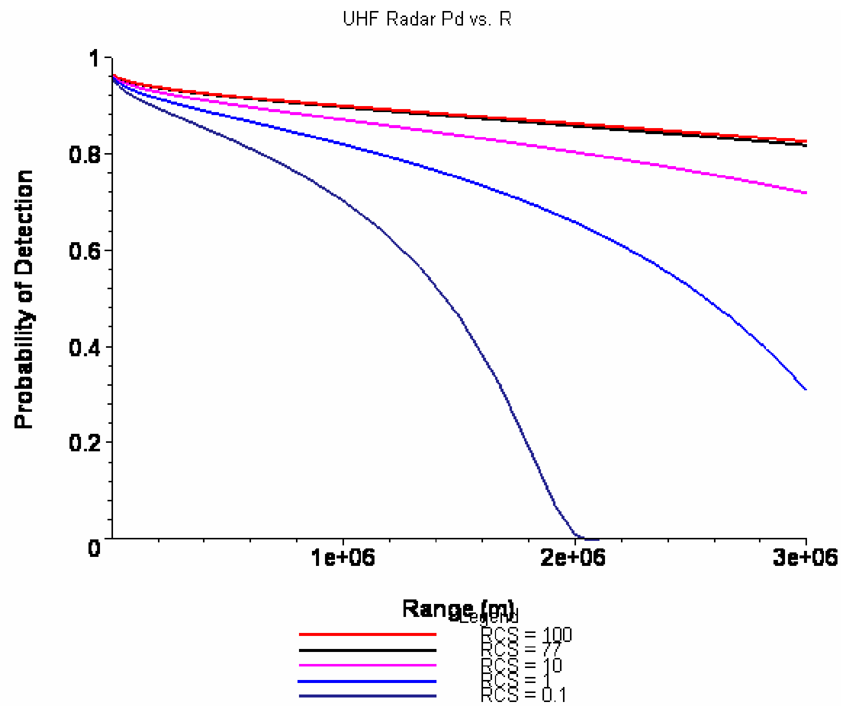


Figure 3 – DARBC P_D vs. Range performance using the UHF spectrum

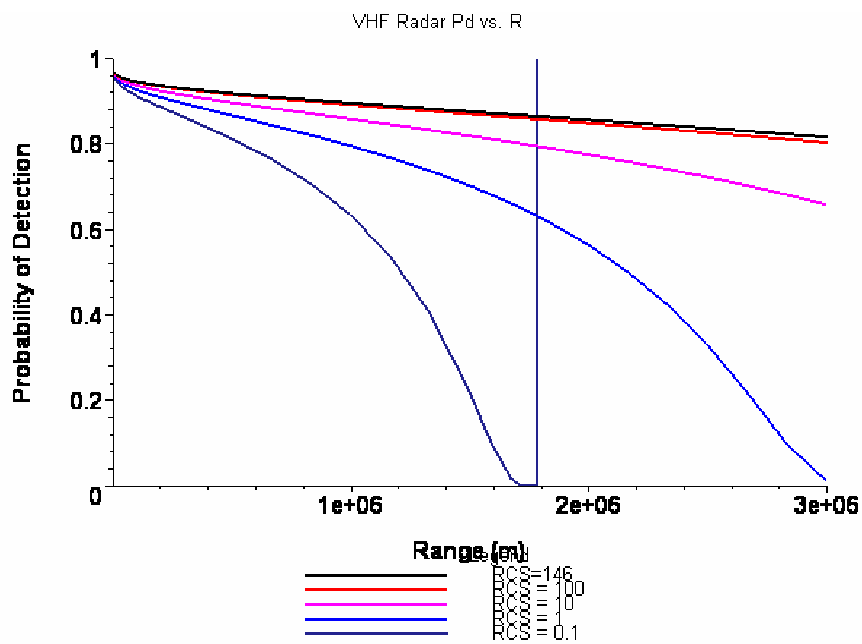


Figure 4 – DARBC P_D vs. Range performance using the VHF spectrum

C. SENSITIVITY ANALYSIS

The current model (using parameters defined in Table 1) of the DARBC shows that the radar system will be capable of meeting its KPP of a 90% P_D at the handoff range (748 km) against a notional ballistic missile target however, sensitivity analysis was performed on various parameters to see how easily P_D could be raised for the DARBC. Power, Gain, and number of elements were analyzed against P_D at the handoff range to see if minor adjustments could increase the predicted performance.

i. Power Sensitivity

Power sensitivity analysis shows that major increases in P_T would not bring the performance of the DARBC up significantly. As you can see in Figures 5 and 6, increased levels in power beyond several tens of kW have a mild affect on P_D. Power levels for the DARBC would have to be raised to an unfeasible level in order to have an increase of 1 – 2 % in P_D.

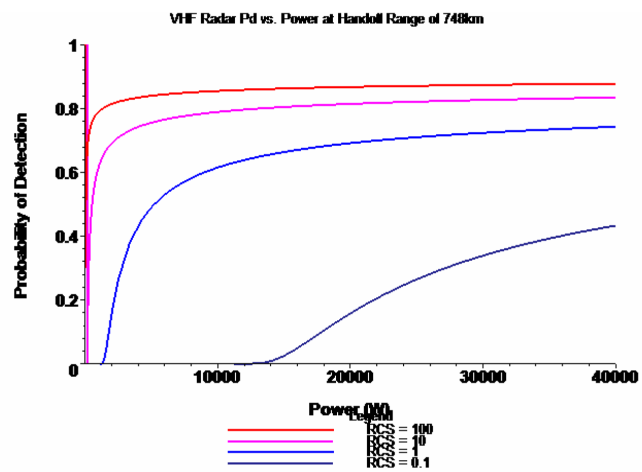


Figure 5 – VHF Radar P_D vs. Power at a range of 748 km

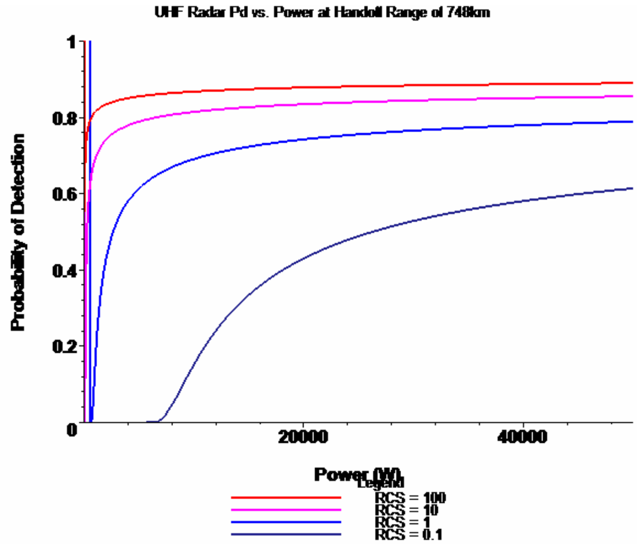


Figure 6 – UHF Radar P_D vs. Power at a range of 748 km

ii. Gain Sensitivity

Gain sensitivity analysis shows that increases in G of about 10dB or so have the ability to increase the performance of the DARBC with some level of significance depending on the RCS of the target. The smaller RCSs will benefit more from this type of adjustment to the radar parameters. See figures 7 and 8 for the gain sensitivity analysis.

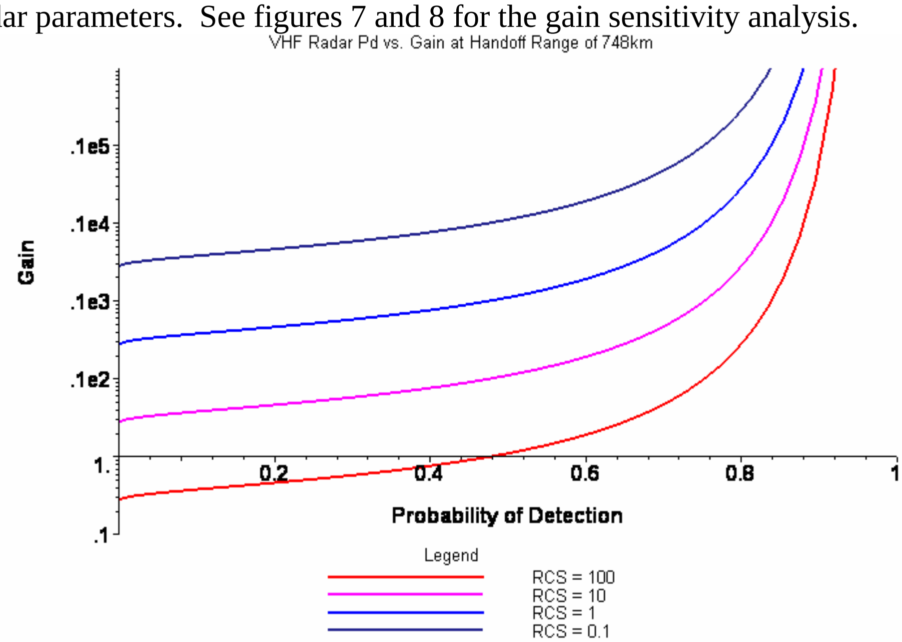


Figure 7 – VHF Gain vs. P_D at a range of 748 km

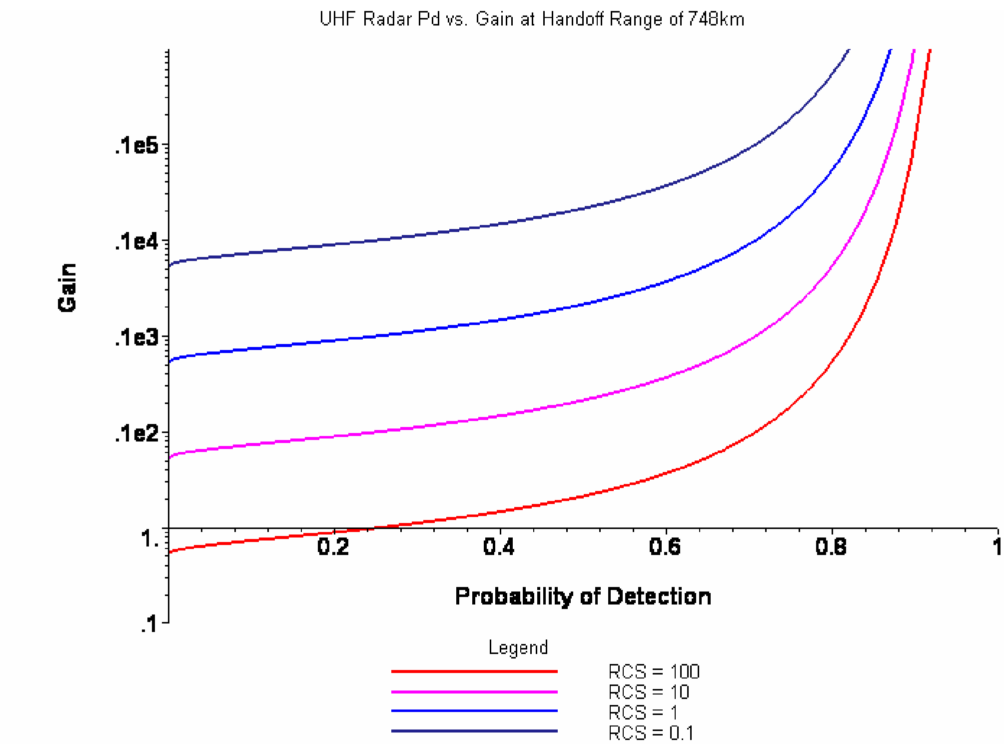


Figure 8 – UHF Gain vs. P_D at a range of 748 km

iii. **Aperstructure Size Sensitivity (number of elements)**

Since G is a function of wavelength (λ) and antenna effective aperture (A_e), further analysis is needed to look into A_e since λ is fixed at the VHF and UHF bands. A_e is a dependent on the number of elements in the array as they are fixed in size. Figure 9 shows the sensitivity curves for number of elements as a function of P_D for the DARBC using the VHF spectrum. There is some level of performance to gain by boosting the number of active elements for the lower RCSs for this system.

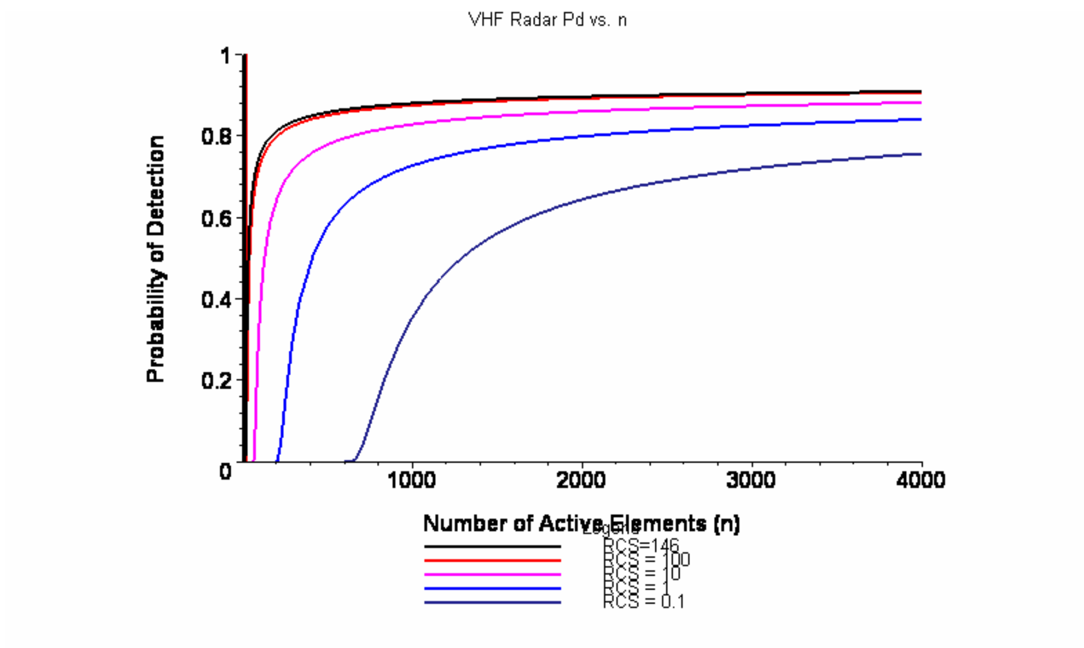


Figure 9 – VHF P_D vs. Number of Elements at a range of 748 km

Results show that an increase in the number of active elements from the value specified in Table 1 will have a minor but significant affect on P_D against targets with lower RCS values, however this sensitivity analysis also shows the impact of having less elements than the number specified in Table 1. Should n be reduced, performance could suffer greatly.

IV. CONCLUSION

Based on the Maple analysis, using parameters listed in Table 1, the calculated handoff range between the DARBC and the S-band radar should be 748 km (Expected Output #2). At 748 km, the S-band radar is able to track a notional ballistic missile target (RCS of 10 m^2) with a P_D of 0.50. At this same range, the DARBC is capable of tracking the same target (RCS of 146m^2 for VHF and 77m^2 for UHF) with a P_D of 0.91 using the parameters listed in Table 1 (Expected Output #1). With these recommended parameters, the performance of the DARBC can be characterized in the P_D vs. Range plots seen in

Figures 3 and 4 (Expected Output #3). Figure 3 is the P_D vs. Range plot for the DARBC operating in the UHF band. Figure 4 is the P_D vs. Range plot for the DARBC operating in the VHF band. Figure 2 is the PD vs. Range plot for the notional S-band radar.

V. APPENDIX – MAPLE SOURCE CODE

Here is the maple source code used to perform the mathematical analysis. Important results are listed in Table 1 and in section IV of this Technote. The maple file will also be imbedded in this document. These same commands were modified to conduct the sensitivity analysis. The sensitivity analysis files will be imbedded in this document only.

<u>DARBC_Radar_Parameters_Final.mws</u>

C:\Documents and Settings\Paul\Deskto

```
> #Naval Postgraduate School (NPS)
> #Masters of Science in Systems Engineering (MSSE)
> #Naval Surface Warfare Center (NSWC) Port Hueneme Division (PHD)
> #Team "R" Capstone Project, Radar Technical Parameters Research
> #23 August, 2006, PRD
>
> restart;  #Reset of Maple's Memory
> #Defining Radar Equation Parameters (see table in technote for definitions)
> P:=500000;p:=3E6;H1:=100;H1V:=146;H1U:=77;H2:=10;H3:=1;H4:=0.1;N:=1;E:=1;K:=1.38065E-23;T:=290;B1:=23000;B2:=44000;B3:=4E6;F:=10^(3/5);fa:=0.01;f1:=216E6;f2:=420E6;f3:=3E9;L1:=100;L2:=5;W1:=40;W2:=5;Ef:=0.7;n:=3411;
```

$$P := 500000$$

$$p := .3\ 10^{7}$$

$$H1 := 100$$

$$H1V := 146$$

$$H1U := 77$$

$$H2 := 10$$

$$H3 := 1$$

$$H4 := .1$$

$$N := 1$$

$$E := 1$$

$$K := .138065\ 10^{-22}$$

$$T := 290$$

$$B1 := 23000$$

$$B2 := 44000$$

$$B3 := .4\ 10^{7}$$

$$F := 10^{(3/5)}$$

$$fa := .01$$

$$f1 := .216\ 10^{9}$$

$$f2 := .420\ 10^{9}$$

$$f3 := .3\ 10^{10}$$

$$L1 := 100$$

$$L2 := 5$$

$$\mathrm{W1} := 40$$

$$\mathrm{W2} := 5$$

$$Ef := .7$$

$$n := 3411$$

```
> WL1:=299792458/f1;
```

$$WL1 := 1.387928046$$

```
> WL2:=299792458/f2;
```

$$WL2 := .7137915667$$

```
> WL3:=299792458/f3;
```

$$WL3 := .09993081932$$

```
> A1:=Ef*(n/2);
```

$$A1 := 1193.850000$$

```
> A2:=Ef*(n/2);
```

$$A2 := 1193.850000$$

```
> A3:=Ef*L2*W2;
```

$$A3 := 17.5$$

```
> G1:=(A1*4*Pi)/(WL1^2):
> G1db:=evalf(10*log10(G1),5);
```

$$G1db := 38.914$$

```
> G2:=(A2*4*Pi)/(WL2^2):
> G2db:=evalf(10*log10(G2),5);
```

$$G2db := 44.689$$

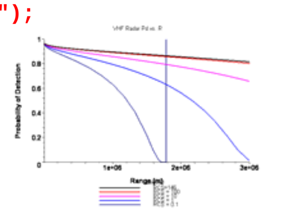
```
> G3:=(A3*4*Pi)/(WL3^2):
> G3db:=evalf(10*log10(G3),5);
```

$$G3db := 43.428$$

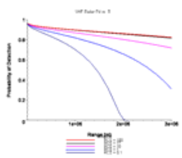
```
> RE1VHF:=(R1)^4=(P*G1*A1*H1V*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 146m^2
> RE1:=(R1)^4=(P*G1*A1*H1*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 100m^2
> REA1:=(R1)^4=(P*G1*A1*H2*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 10m^2
> REB1:=(R1)^4=(P*G1*A1*H3*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 1m^2
> REC1:=(R1)^4=(P*G1*A1*H4*N*E)/(((4*Pi)^2)*K*T*B1*F*S1):# VHF Radar Equation using RCS of 0.1m^2
>
```

```
> RE1U:=(R2)^4=(P*G2*A2*H1*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 100m^2
> RE1UHF:=(R2)^4=(P*G2*A2*H1U*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 77m^2
> REA1U:=(R2)^4=(P*G2*A2*H2*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 10m^2
> REB1U:=(R2)^4=(P*G2*A2*H3*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 1m^2
> REC1U:=(R2)^4=(P*G2*A2*H4*N*E)/(((4*Pi)^2)*K*T*B2*F*S2):# UHF Radar Equation using RCS of 0.1m^2
>
> RE1S:=(R3)^4=(p*G3*A3*H1*N*E)/(((4*Pi)^2)*K*T*B3*S3):# S-Band Radar Equation using RCS of 100m^2
> REA1S:=(R3)^4=(p*G3*A3*H2*N*E)/(((4*Pi)^2)*K*T*B3*F*S3):# S-Band Radar Equation using RCS of 10m^2
> REB1S:=(R3)^4=(p*G3*A3*H3*N*E)/(((4*Pi)^2)*K*T*B3*F*S3):# S-Band Radar Equation using RCS of 1m^2
> REC1S:=(R3)^4=(p*G3*A3*H4*N*E)/(((4*Pi)^2)*K*T*B3*F*S3):# S-Band Radar Equation using RCS of 0.1m^2
>
>
> P2VHF:=solve(RE1VHF,S1):
> P3VHF:=10*log10(P2VHF):
> RE2VHF:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=P3VHF:
> P4VHF:=solve(RE2VHF,D1):
>
> #P1:=eval(RE1):
> P2:=solve(RE1,S1):
> P3:=10*log10(P2):
> RE2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=P3:
> P4:=solve(RE2,D1):
>
> #PA1:=eval(REA1):
> PA2:=solve(REA1,S1):
> PA3:=10*log10(PA2):
> REA2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=PA3:
> PA4:=solve(REA2,D1):
>
> #PB1:=eval(REB1):
> PB2:=solve(REB1,S1):
> PB3:=10*log10(PB2):
> REB2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=PB3:
> PB4:=solve(REB2,D1):
>
> #PC1:=eval(REC1):
> PC2:=solve(REC1,S1):
> PC3:=10*log10(PC2):
> REC2:=(10*log10(fa)-10*log10(D1))/(10*log10(D1))=PC3:
> PC4:=solve(REC2,D1):
>
> #P1U:=eval(RE1U):
> P2U:=solve(RE1U,S2):
> P3U:=10*log10(P2U):
> RE2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=P3U:
> P4U:=solve(RE2U,D2):
>
>
> P2UHF:=solve(RE1UHF,S2):
> P3UHF:=10*log10(P2UHF):
> RE2UHF:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=P3UHF:
> P4UHF:=solve(RE2UHF,D2):
>
> #PA1U:=eval(REA1U):
> PA2U:=solve(REA1U,S2):
> PA3U:=10*log10(PA2U):
```

```
> REA2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=PA3U:
> PA4U:=solve(REA2U,D2):
>
> #PB1U:=eval(REB1U):
> PB2U:=solve(REB1U,S2):
> PB3U:=10*log10(PB2U):
> REB2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=PB3U:
> PB4U:=solve(REB2U,D2):
>
> #PC1U:=eval(REC1U):
> PC2U:=solve(REC1U,S2):
> PC3U:=10*log10(PC2U):
> REC2U:=(10*log10(fa)-10*log10(D2))/(10*log10(D2))=PC3U:
> PC4U:=solve(REC2U,D2):
>
> #P1S:=eval(RE1S):
> P2S:=solve(RE1S,S3):
> P3S:=10*log10(P2S):
> RE2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=P3S:
> P4S:=solve(RE2S,D3):
>
> #PA1S:=eval(REA1S):
> PA2S:=solve(REA1S,S3):
> PA3S:=10*log10(PA2S):
> REA2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=PA3S:
> PA4S:=solve(REA2S,D3):
>
> #PB1S:=eval(REB1S):
> PB2S:=solve(REB1S,S3):
> PB3S:=10*log10(PB2S):
> REB2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=PB3S:
> PB4S:=solve(REB2S,D3):
>
> #PC1S:=eval(REC1S):
> PC2S:=solve(REC1S,S3):
> PC3S:=10*log10(PC2S):
> REC2S:=(10*log10(fa)-10*log10(D3))/(10*log10(D3))=PC3S:
> PC4S:=solve(REC2S,D3):
>
> plot([P4VHF,P4,PA4,PB4,PC4],R1=0..8000000,D1=0..1,xtickmarks=3,labels=["Range
(m)","Probability of
Detection"],labeldirections=[HORIZONTAL,VERTICAL],legend=["RCS=146","RCS = 100","RCS =
10","RCS = 1","RCS =
0.1"],view=[0..3E6,0..1],color=[black,red,magenta,blue,navy],thickness=2,font=[HELVETICA,
BOLD,12],title="VHF Radar Pd vs. R");
```

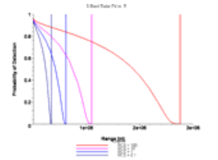


```
> plot([P4U,P4UHF,PA4U,PB4U,PC4U],R2=0..8000000,D2=0..1,xtickmarks=3,labels=["Range
(m)","Probability of Detection"],labeldirections=[HORIZONTAL,VERTICAL],legend=["RCS =
100","RCS = 77","RCS = 10","RCS = 1","RCS =
0.1"],view=[0..3E6,0..1],color=[red,black,magenta,blue,navy],thickness=2,font=[HELVETICA,
BOLD,12],title="UHF Radar Pd vs. R");
```



```
> plot([P4S,PA4S,PB4S,PC4S],R3=0..8000000,D3=0..1,xtickmarks=3,labels=["Range
(m)","Probability of Detection"],labeldirections=[HORIZONTAL,VERTICAL],legend=["RCS =
```

```
100","RCS = 10","RCS = 1","RCS =
0.1"],view=[0..3E6,0..1],color=[red,magenta,blue,navy],thickness=2,font=[HELVETICA,BOLD,1
2],title="S-Band Radar Pd vs. R");
>
```



```
> eval(PB4S,R3=425000);#S-Band Radar's "Range" using 1m^2 RCS. (Range is R (450km))
(Result should be 0.5)
```

$$.4904985725$$

```
> eval(PA4S,R3=748000);#S-Band Radar's max Range for Handoff (Handoff Range is R (748km))
(Result should be 0.5)
```

$$.5000286862$$

```
> VHFPsubD:=evalf(eval(P4VHF,R1=748000),5);#VHF Pd at handoff range vs. Ballistic Missile
(146m^2 RCS)
```

$$VHFPsubD := .90616$$

```
> UHFPsubD:=evalf(eval(P4UHF,R2=748000),5);#UHF Pd at handoff range vs. Ballistic Missile
(77m^2 RCS)
```

$$UHFPsubD := .90651$$

```
>
```

Power Sensitivity Analysis

C:\Documents and
Settings\Paul\Desktop

Gain Sensitivity Analysis

C:\Documents and
Settings\Paul\Desktop

Number of Elements Sensitivity Analysis

C:\Documents and
Settings\Paul\Desktop

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D. DARBC-TN-06A OODA LOOP MODELING

Document Type: Technical Note	Document Number: DARBC-TN-06A
Program: DARBC	**Classification:** Unclassified

TITLE: Observe, Orient, Decide, Act (OODA) Loop Reaction Time analysis for the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC)

PROBLEM STATEMENT:

The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter Stealth (DARBC) system will require OODA loop modeling to determine the reaction time from first target detection to interceptor launch. This Technote will address the analysis for OODA loop modeling to simulate the reaction time of the DARBC system from the operational viewpoint with targets detected at various ranges. This study is necessary to ensure realistic operational scenarios for DARBC system are considered in the development of this Radar system.

Expected Outputs of study:

List of attributes required to generate a OODA loop model
Listing of simulated result of reaction time from detection to engagement for two different scenarios
Future studies to further enhance the OODA loop modeling

Prepared by: Jack Chung	**Original Date:** 28 August, 2006	**Comments:** Initial Submission of document
Prepared by: Bob Hazle	**Original Date:**	
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Ian Barford	**Date:**	
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 2 September, 2006	Final Review of document
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

This paper provides two scenarios and their reaction times for evaluating the OODA loop model for the DARBC Radar System. The purpose of the modeling is to measure the benefit of the DARBC radar while considering the operational environment. The simulation will consider all elements involved in the prosecution of an engagement of a ballistic missile and will use targets which are detected randomly at various ranges in order to evaluate a normalized reaction time.

II. Background

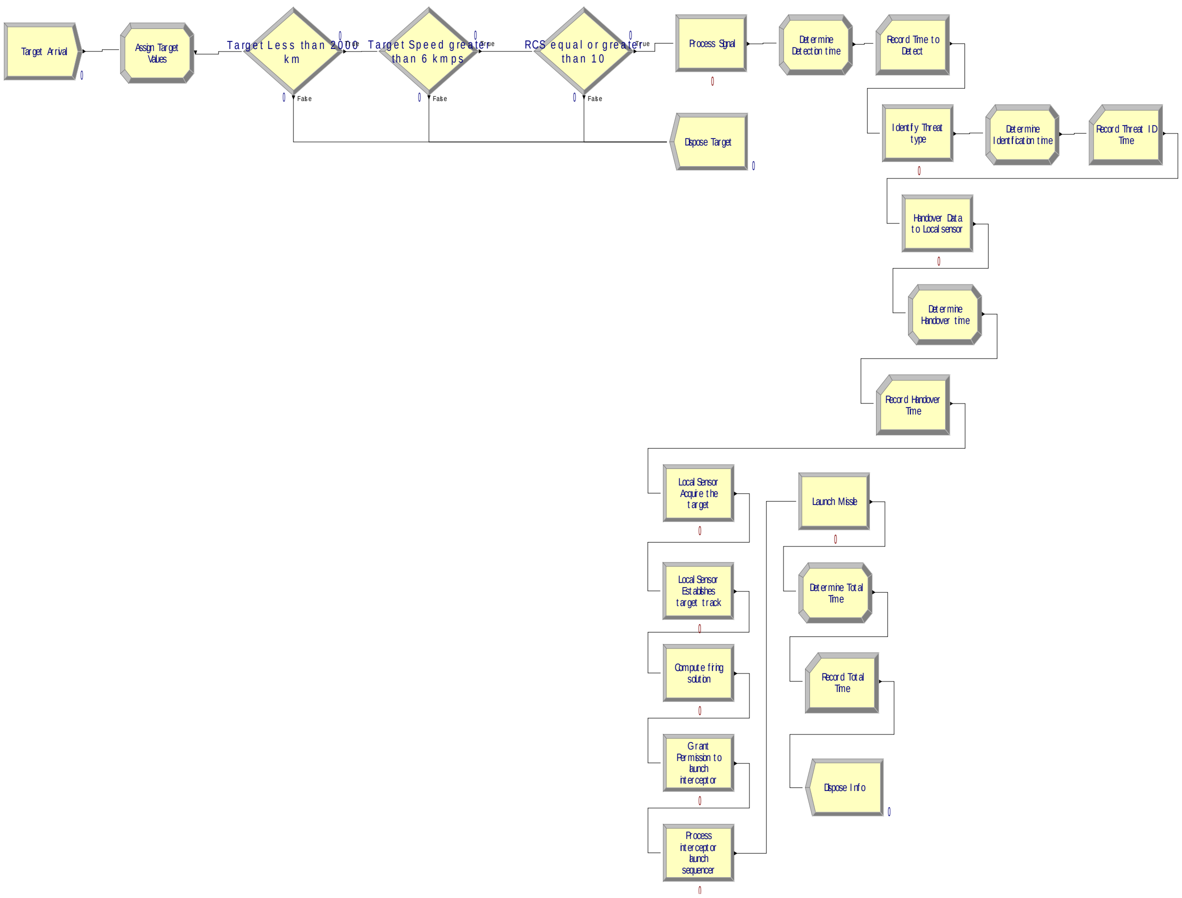
Reference (a) provided methods and procedures for using the ARENA 10.0 simulation software for simulating the OODA loop model. Basic processing modules from the ARENA simulation software were used to assess the OODA loop model. The following table provides definition for the modules used:

Module	Definition (see Ref (b))
Create	This module is intended as the starting point for entities in a simulation model. Entities are created using a schedule or based on a time between arrivals. Entities then leave the module to begin processing through the system. The entity type is specified in this module.
Assign	This module is used for assigning new values to variables, entity attributes, entity types, entity pictures, or other system variables. Multiple assignments can be made with a single Assign module.
Decide	This module allows for decision-making processes in the system. It includes options to make decisions based on one or more conditions (e.g., if entity type is Gold Card) or based on one or more probabilities (e.g., 75% true; 25% false). Conditions can be based on attribute values (e.g., Priority), variable values (e.g., Number Denied), the entity type, or an expression (e.g., NQ (ProcessA.Queue)).
Process	This module is intended as the main processing method in the simulation. Options for seizing and releasing resource constraints are available. Additionally, there is the option to use a "submodel" and specify hierarchical user-defined logic. The process time is allocated to the entity and may be considered to be value added, non-value added, transfer, wait or other. The associated cost will be added to the appropriate category.
Record	This module is used to collect statistics in the simulation model. Various types of observational statistics are available, including time between exits through the module, entity statistics (time, costing, etc.), general observations, and interval statistics (from some time stamp to the current simulation time). A count type of statistic is available as well. Tally and Counter sets can also be specified.
Dispose	This module is intended as the ending point for entities in a simulation model. Entity statistics may be recorded before the entity is disposed.

Table 1.

II. DISCUSSION

The Arena ® Model analysis software was used to simulate the DARBC detection time, data handover time to local sensor, and the local fire control loop engagement sequence time. The following figures represent the OODA loop configurations for the DARBC and local sensor (Figure 1) and the local sensor only (Figure 2).



Arena Model 1 (Ref(c))

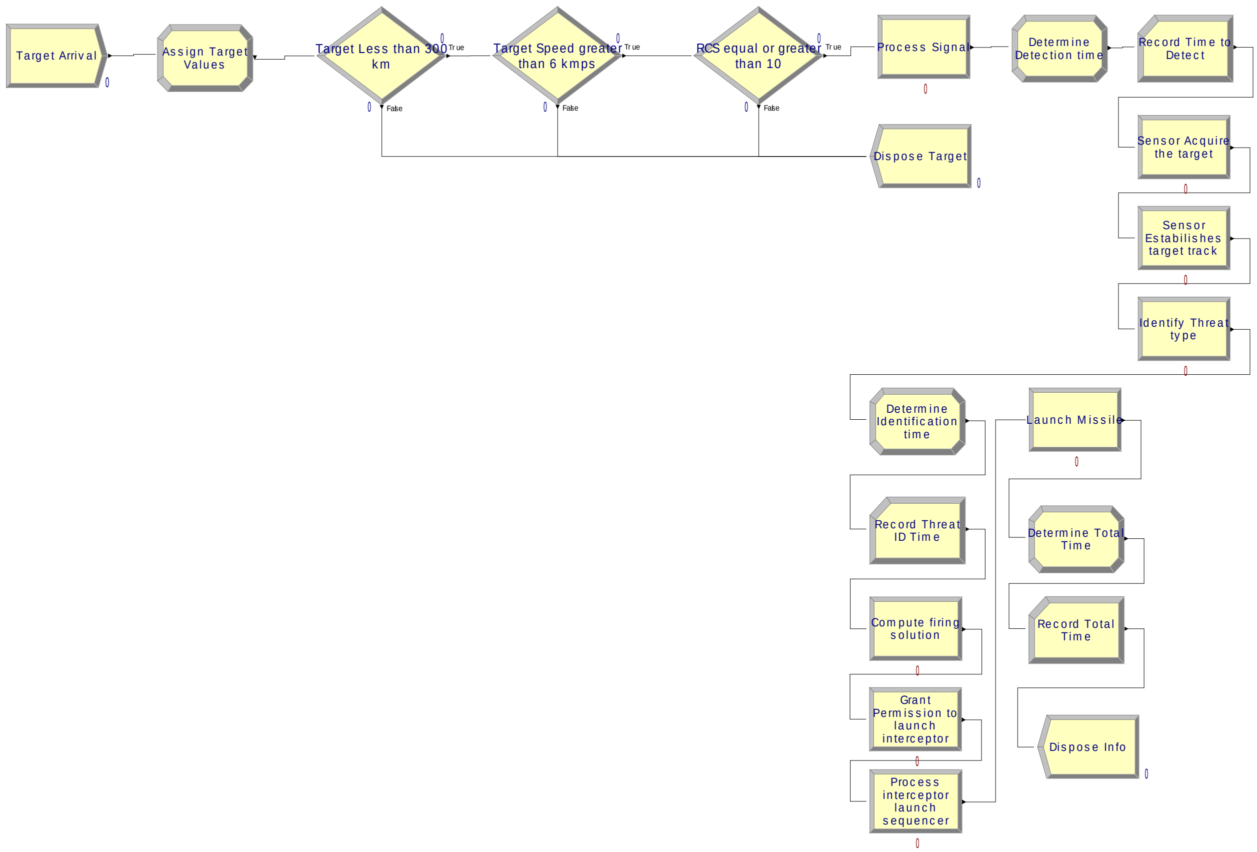


Figure 2. Model 2 (Ref (c))

The OODA loop models were executed for ten repetitions for each of the two scenarios. The first scenario, figure 1, calculated the average DARBC detection time and total time from the DARBC's first detection of the threat to handover of threat data to local sensor and to the launch of interceptor from the local ship to disable the ballistic target.

The second scenario, figure 2, calculates the local sensor only average detection time and average engagement time to disable the ballistic target.

The following notional attributes were used to model the OODA loop:

Arrival Time: TNOW

RCS: Uniformly Distributed between 1 to 300 m^2

Target Speed: Uniformly Distributes between 1 to 10 km/sec

Target from Own-ship: Uniformly Distributed between 500 to 5000 km (DARBC aided)

Target from Own-ship: Uniformly Distributed between 50 to 300 km (Local Sensor only)

The following are the analysis results from the model for both VHF and UHF:

DARBC Radar Aiding Local Sensor	Average (sec)	Minimum Value (sec)	Maximum Value (sec)
Record Time to Detect	1.4573664	1.0087536	1.983207
Record Handover Time	5.652	0.629757	9.99
Local System Engagement Time	9.0906336	8.7594894	9.008793
Record Total Time	16.2	10.398	20.982

Table 3.

Local Sensor Only	Average (sec)	Minimum Value (sec)	Maximum Value (sec)
Record Time to Detect	1.5256	1.013	1.9939
Record Total Time	10.554	8.136	12.81

Table 4.

Table 3 indicated that DARBC Radar on average takes 1.46 seconds to detect a high velocity target in the range between 500 km to 2000 km. Total time from first detection by DARBC to the time when data handover occurs to the local sensor in order to launch the interceptor is 16.2 seconds.

Table 4 indicated that local sensor without aid of the DARBC radar takes average of 1.52 seconds to detect a high velocity target in the range between 50 km to 300 km. The total time from the first detection to interceptor launch is 10.55 seconds. The comparison indicated that with the aid of DARBC radar the average local system engagement time improves from 10.55 seconds to 9.09 seconds.

III. CONCLUSION

The OODA model indicated that average DARBC radar assisted reaction time is less than without the use of it. With the DARBC present, the overall reaction time to the threat was increased by 53.5% on average. One draw back to this approach is that the OODA models presented here do not take into considerations of earth curvature, ballistic target flight path, earth gravity, and vary target velocity. However, as long as the same approach is taken for both systems, with the DARBC and without, a significant improvement is seen in the overall reaction time. In the future, studies and simulations need to include these more realistic technical parameters to further improve the OODA model in order to simulate a more realistic operational environment.

References

a. Simulation with ARENA, third edition, W. David Keltion, Randall P. Sadowski, David T. Sturrock.
b. ARENA 10.0 on-line help menu.
c. ARENA file: track_model_NPS_without_DARBC_Aid_.doe; track_model_NPS_wiith_DARBC_Aid_.doe;

E. DARBC-TN-06B REACTION TIME MODELING

Document Type: Technical Note		**Document Number:** DARBC-TN-06B
Program: DARBC		**Classification:** Unclassified

TITLE: Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) Enhancement to Reaction Time

PROBLEM STATEMENT: The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) is an early warning system. It does not itself control a weapon. So the most significant benefit it can provide is more time to react to an attack. The intent is to measure this enhancement in two ways: extra evaluation time and extra area coverage.

Expected Outputs of Study:

- Analysis of Theater Ballistic Missile (TBM) flight paths relative to maximum detection ranges for the DARCB and the aided and unaided notional weapons control radar.
- Time-range plot for significant launch ranges of short-, intermediate-, and medium-range TBMs.
- Calculated benefits of evaluation time and extra area coverage for short, intermediate, and medium-range TBMs.

Prepared by: David Bedford	**Original Date:** 30 August, 2006	**Comments:** Submission of 4th revision.
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Ian Barford	**Date:**	
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 2 September, 2006	Final comments made.
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

The purpose of this Technote is to describe and calculate the comparative benefit in reaction time of a ship equipped with the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) over one without.

II. BACKGROUND

For the purpose of this technote the subject ship is, in all cases, equipped with a weapon system. The weapon's range exceeds the tracking range of the Weapon Control Radar (WCR). The WCR has two track range parameters. The first is the range at which the unaided WCR can detect, acquire, and track a TBM. The second range is achieved when the WCR receives a cue or designation from another source, the DARBC in this case. For this investigation the ranges of our notional WCR are 300 km unaided and 748 km aided[122].

The calculations made in this technote are based on some assumptions supported by a Congressional Budget Office study. According to the study a typical TMB burnout velocity ranges from 6 to 7 km/sec. Because the study is two years old and the DARBC is a future system the high end of the range, 7.5 km/sec is used. As shown in the Team R DARBC Concept Development Document (CDD), the ranges of TBMs are up to 1000 km for a Short Range Ballistic Missile (SRBM), between 1000 and 3000 km for a Medium Range Ballistic Missile (MRBM), between 3000 and 5500 km for an Intermediate Range Ballistic Missile (IRBM)[123]. Again high range values of 1000, 3000, and 5500 and apogee values of 160, 500, and 900 km are used to compensate for future advances in TBM design[124].

Flight path calculations can be complex. They can be based on a rotating, oblate earth with a four-thirds aspect ratio. However, this evaluation is based on a flat, non-rotating earth. The equation used for the flight path of a TBM is elliptical in the form:

$$\boxed{y = Y_c + b\sqrt{1 - \frac{(x - X_c)^2}{a^2}}}$$

Where

x is the horizontal (range) axis.

y is the vertical (altitude) axis.

Y_c is the vertical center of the flight path ellipse in kilometers from the ship due to the curvature of the earth (assigned 0 in this analysis).

Ship is always at x = 0, y = 0.

ADJUSTABLE VARIABLES

X_c is the horizontal center of the flight path ellipse in kilometers from the ship.

a is the semi-major (horizontal) axis of the ellipse in km.

b is the semi-minor (vertical) axis of the ellipse in km.

R is the radius of the earth in km.

Aided R_D is the maximum acquisition range of the WCR when aided by a DARBC designation.
Un-aided R_D is the maximum acquisition range of the un-cued WCR.

In conducting this analysis, the range of each TBM is divided into 1000 segments. The length of the chord across each flight path segment is calculated and assumed to be a good estimate of the length of the flight path arc. Next the chord length is divided by the TBM velocity to determine the time taken to travel that segment of the flight path and to maintain a running total flight time. The range is then calculated using the x and y coordinates of the end of the segment, which is then used to calculate the change in range for that segment. Total time for each of the three range-spaces was calculated as a sum of the segment times for applicable flight path segments. A segment's flight path was determined to be applicable to a range-space as follows:

1. Range-Space #1: 0 km out to the Unaided R_D
    a. The segment ends within the range-space, or,
    b. Both
        i. The segment ends in range-space #2 on the outbound leg, and,
        ii. The range-space #1 time is greater than 0
2. Range-Space #2: Unaided R_D out to the Aided R_D
    a. The segment ends within the range-space, and
    b. Either
        i. The segment ends in range-space #2 on the inbound leg, or,
        ii. The range-space #1 time is equal to 0
3. Range-Space #3: Aided R_D out to the DARBC R_D
    a. The segment ends in range-space #3 on the inbound leg

The justification for 1.b above is that if a target has been in range-space #1, the WCR is already tracking it and is capable of maintaining that track out to Aided R_D. The justification for 2.b above is that the unaided WCR is not capable of acquiring a target in range-space #2. So, if the target has not yet entered range-space #1, acquiring it with the WCR is only possible if the WCR is aided by the DARBC. Criterion 3.a above is justified because an outbound target in range-space #3 is un-engagable.

This analysis does not account for the acceleration of the TBM. It is assumed to be at full speed immediately after launch. This assumption makes the analysis much simpler and the errors it induces are of smaller magnitude than those that result, or would result from uncertainty about velocity and acceleration values and launch angle. This assumption also leads the results of this analysis to be more conservative. If the target initial velocity was zero and it accelerated to full speed at some later time, the time-benefit from the DARBC would be greater.

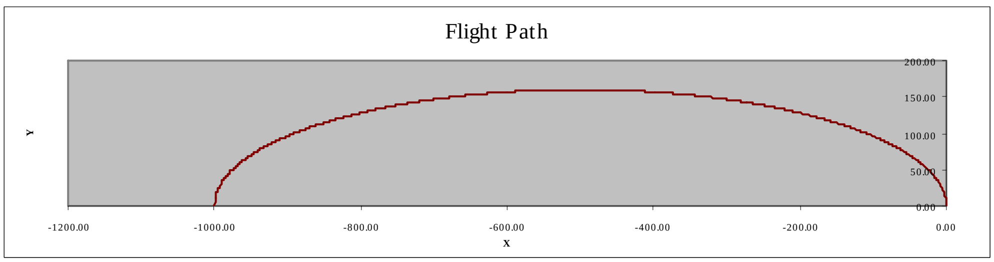
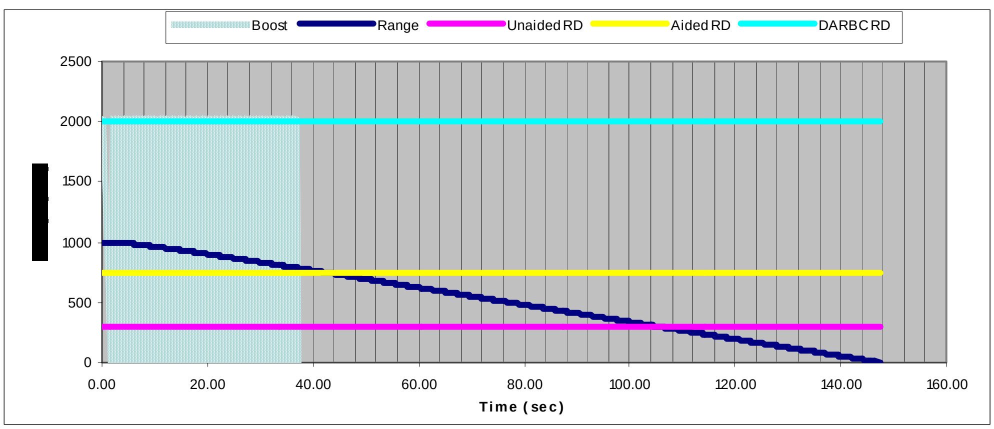
Because the objective of this analysis was to identify engagability gains attributable to the DARBC, the analysis only considered TBMs that could be engaged, i.e., those with launch ranges for which the flight path at least entered the Aided R_D. The Excel analysis

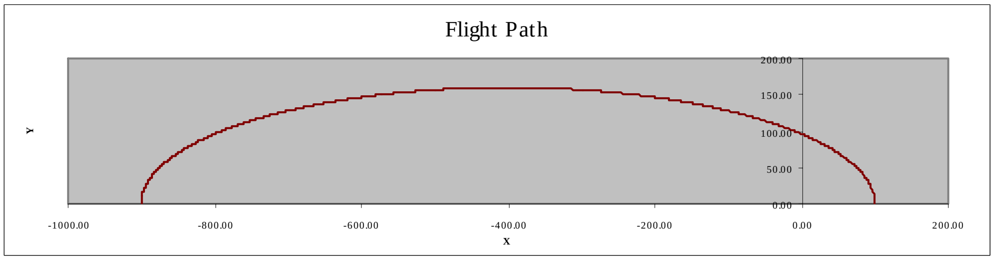
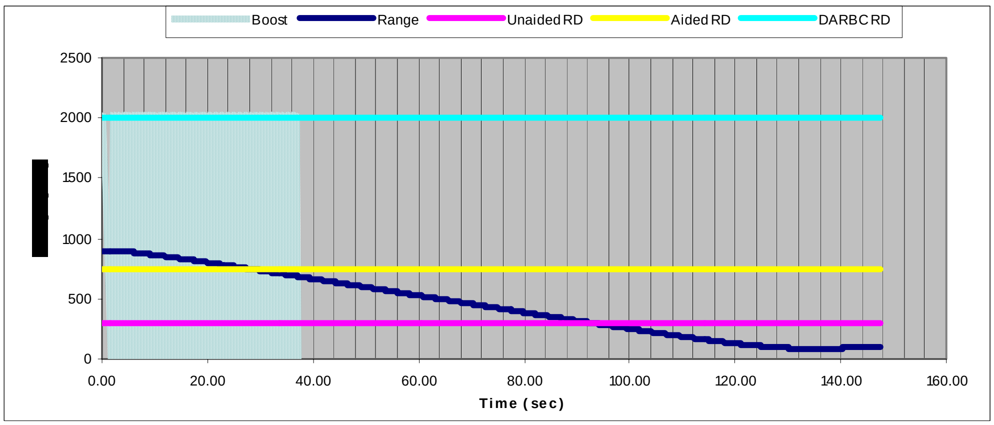
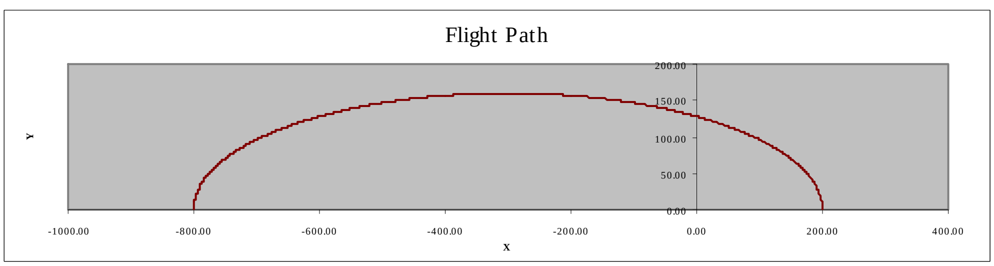
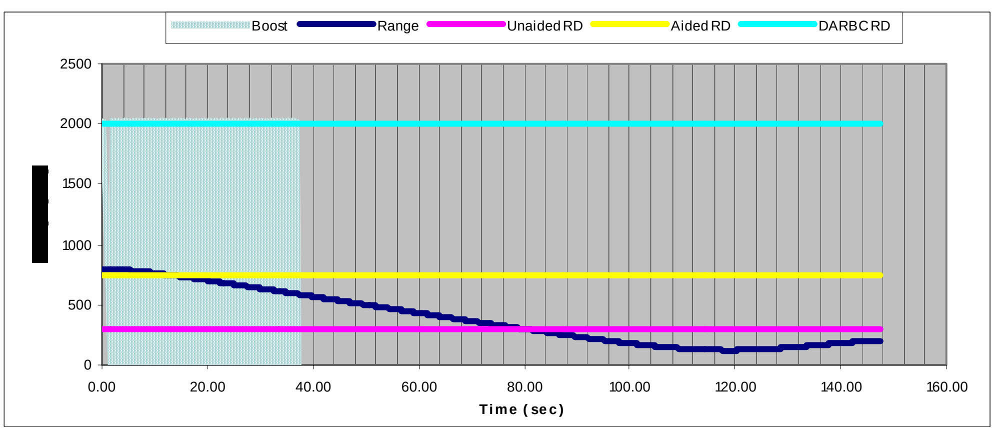
tool allows the boost phase duration to be set as a percentage of the total flight time. For this analysis, boost phase duration was set at 25% and flight paths are only analyzed from launch to the end of boost phase because the DARBC main goal is to provide boost phase intercepts.

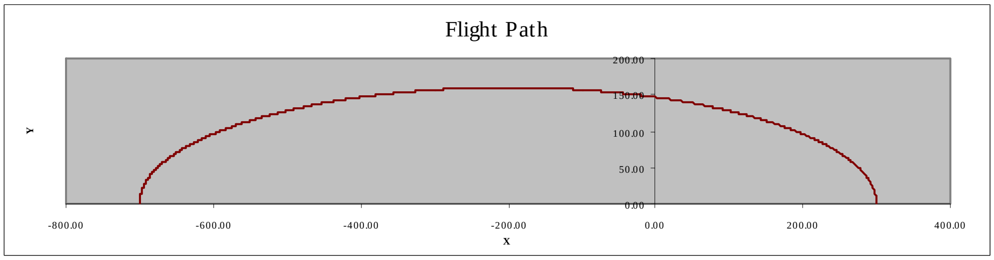
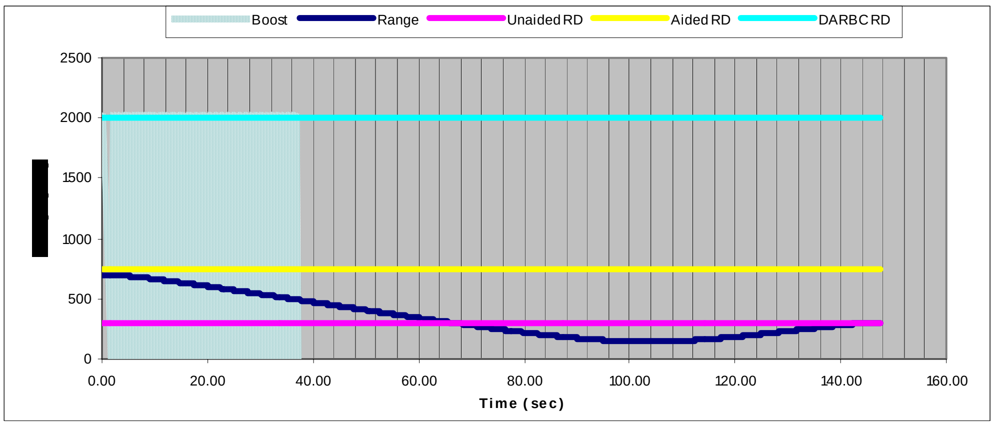
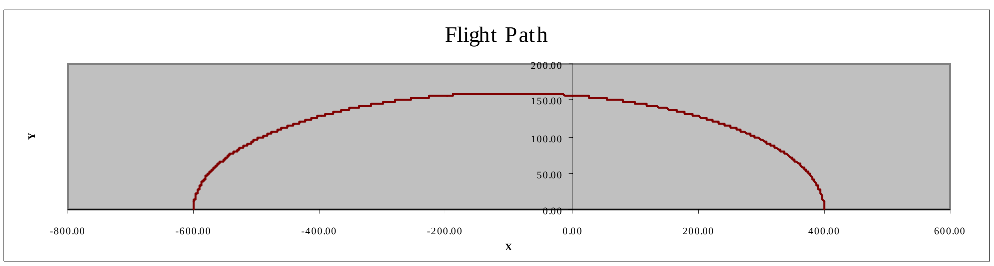
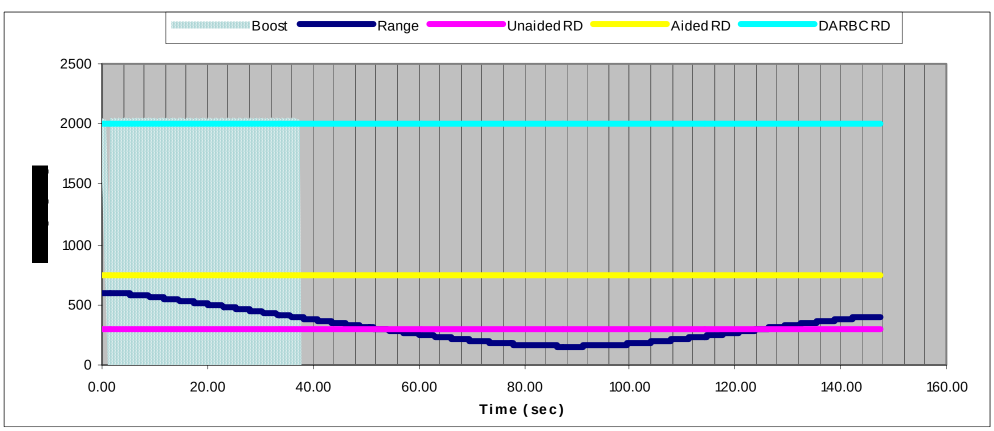
III. DISCUSSION

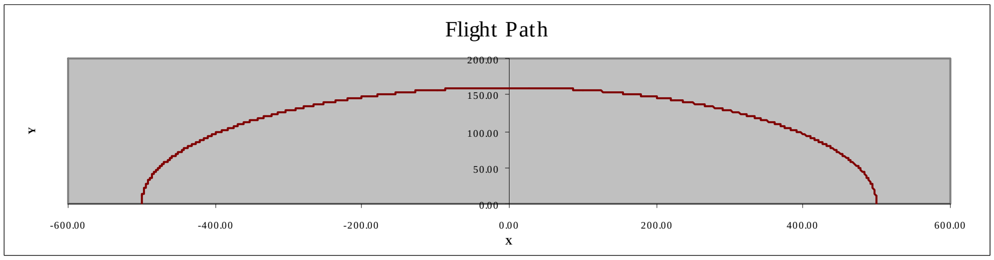
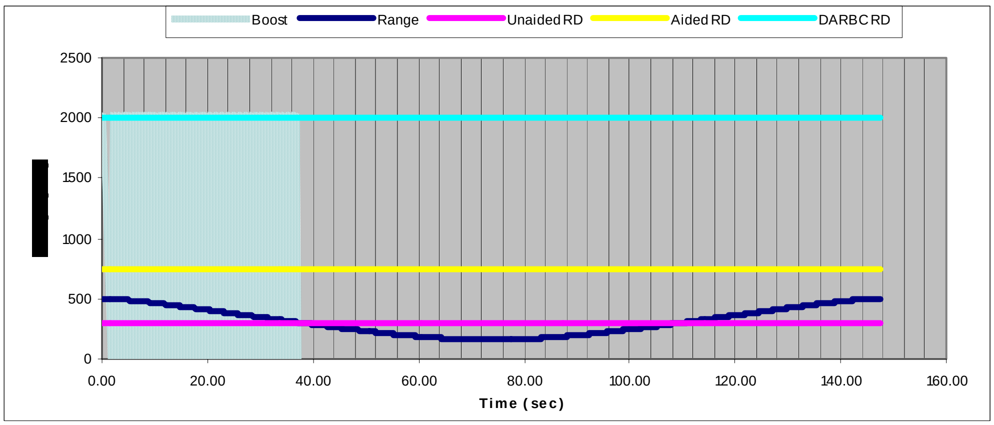
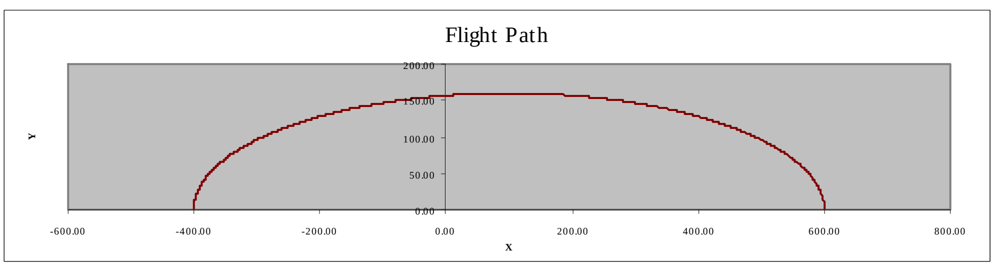
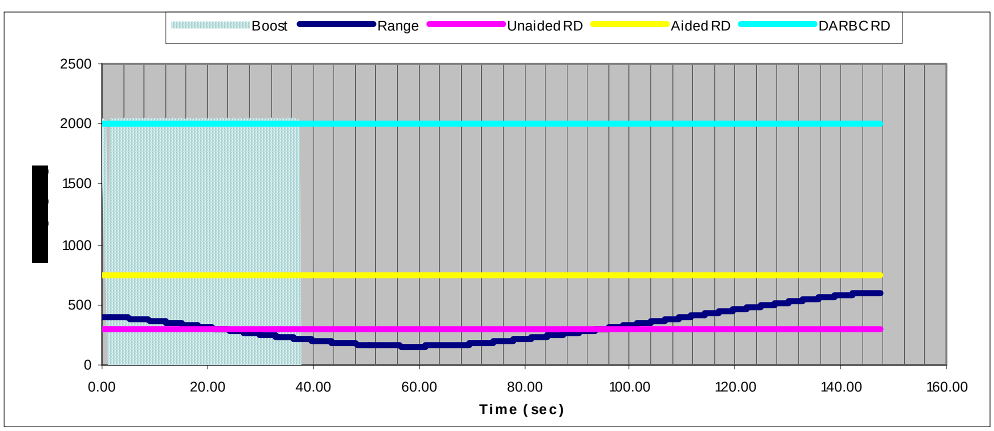
The figures in Tables 7, 8, and 9 show the flight paths and time-range plots for Short-, Medium-, and Intermediate-Range Ballistic Missiles, respectively. The launch ranges shown were selected to present an evenly spaced coverage of launch ranges that present some engagability time. For each flight path plot, the DARBC ship is located at the origin of the axes.

Table 5. SRBM Flight Paths and Time-Range Plots

Launch Range	**SRBM**
1000 km	 

Launch Range	**SRBM**
900 km	 
800 km	 

Launch Range	SRBM
700 km	 
600 km	 

Launch Range	SRBM
500 km	 
400 km	 

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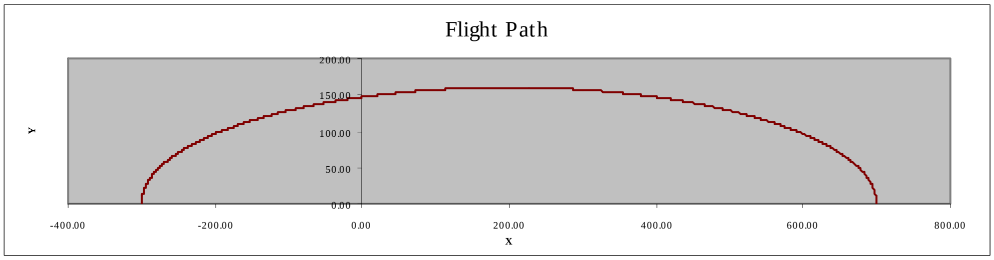
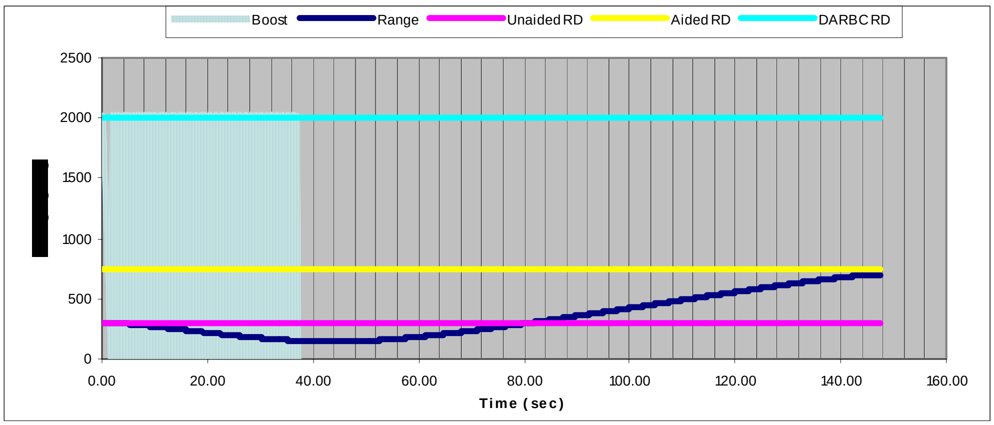
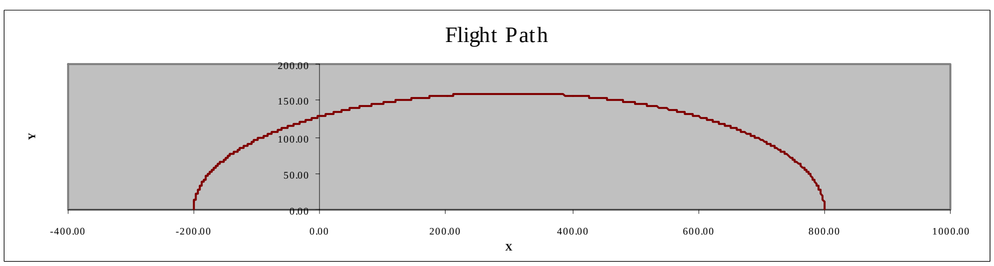
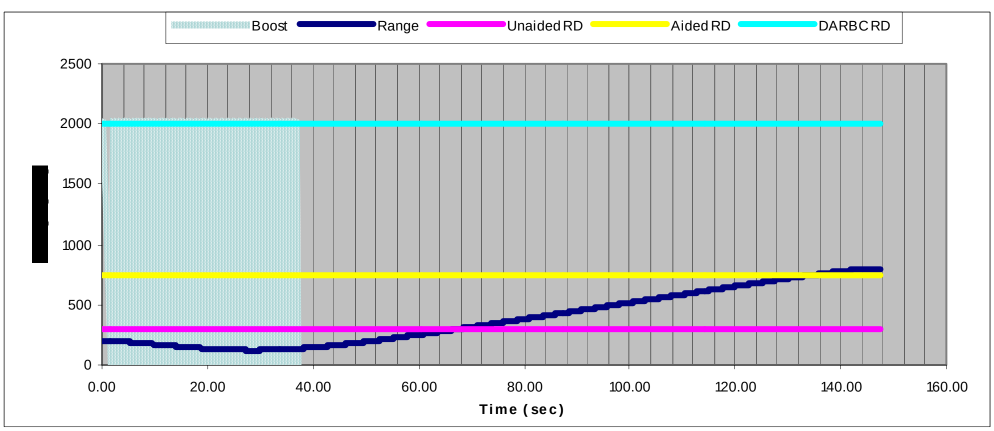




</td></tr>
<tr><td>200 km</td><td>




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<table>
<tr><th>Launch Range</th><th>SRBM</th></tr>
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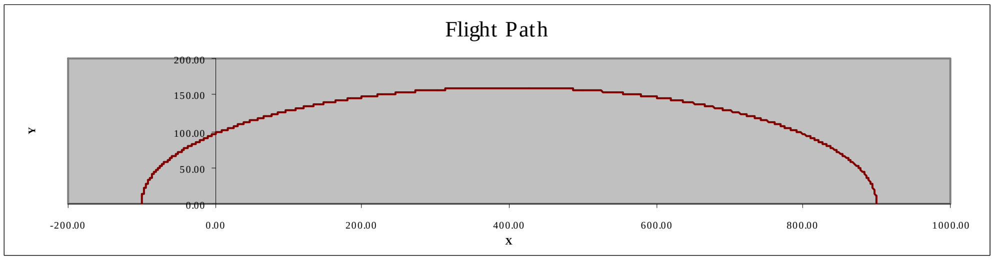
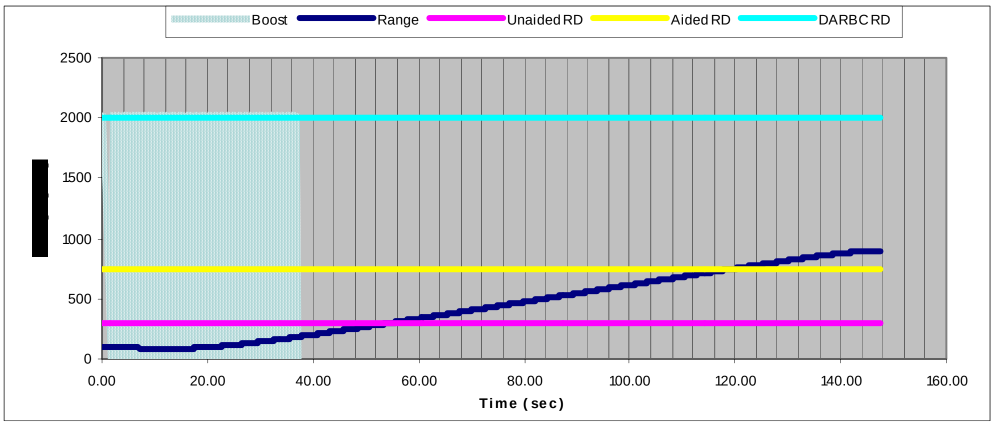
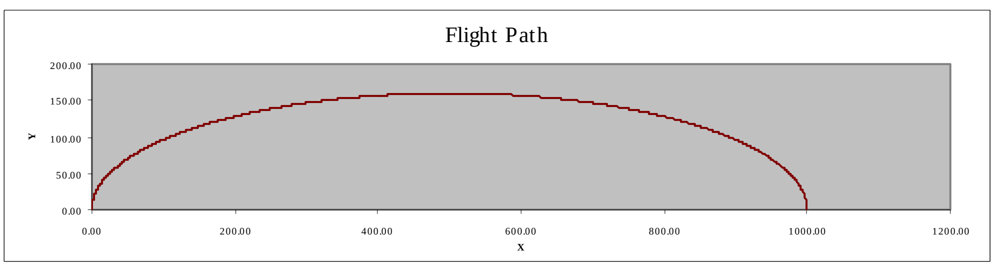
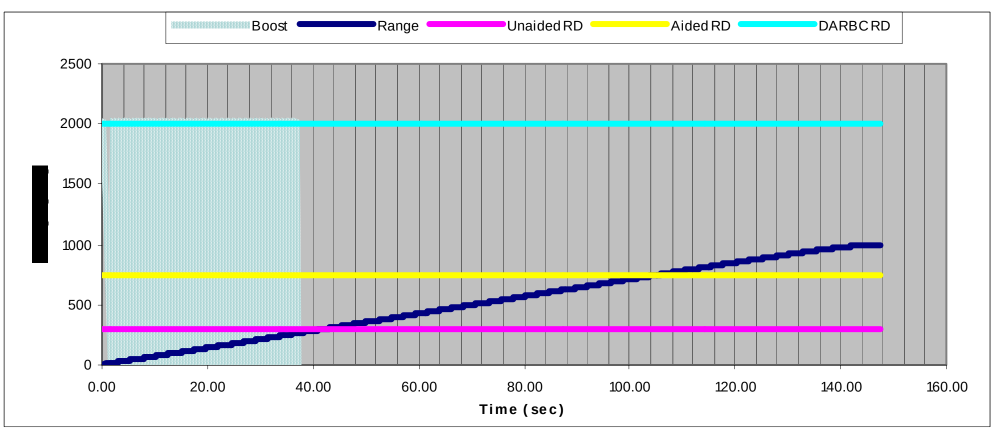




</td></tr>
<tr><td>0 km</td><td>




</td></tr>
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Table 6. MRBM Flight Paths and Time-Range Plots

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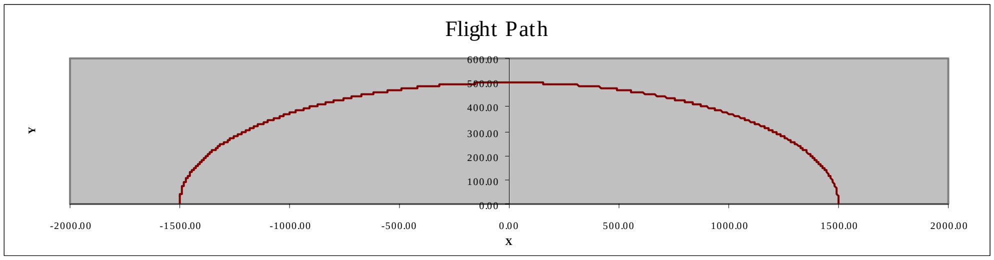

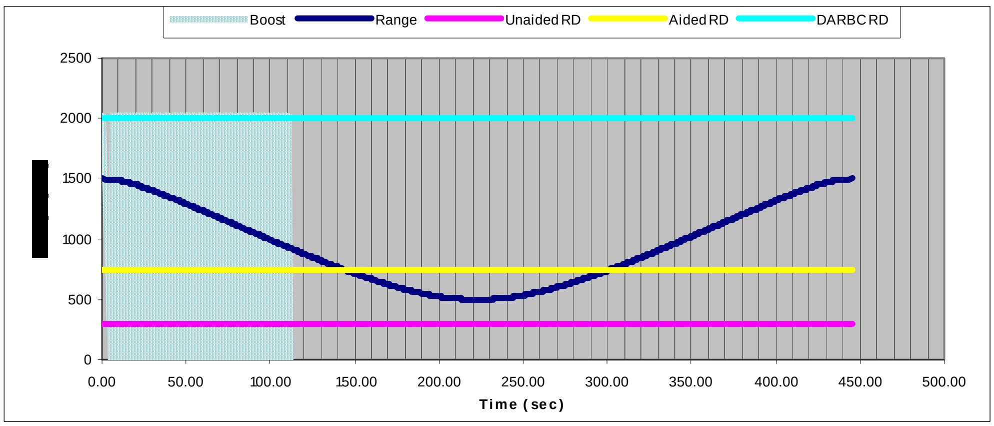

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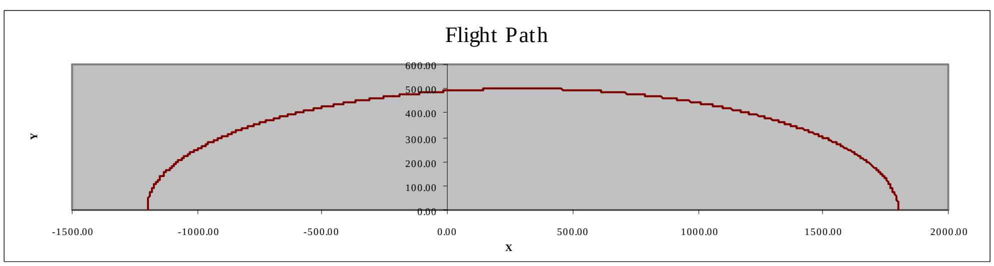
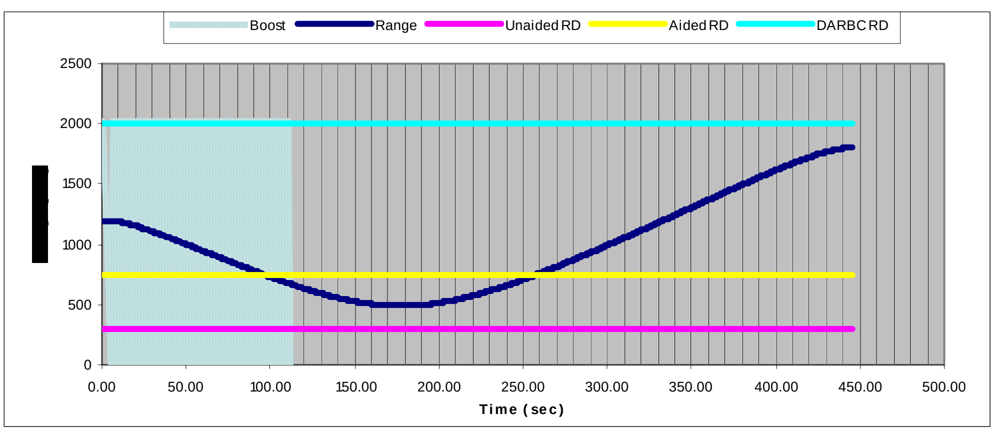
<tr><td>1200 km</td><td>




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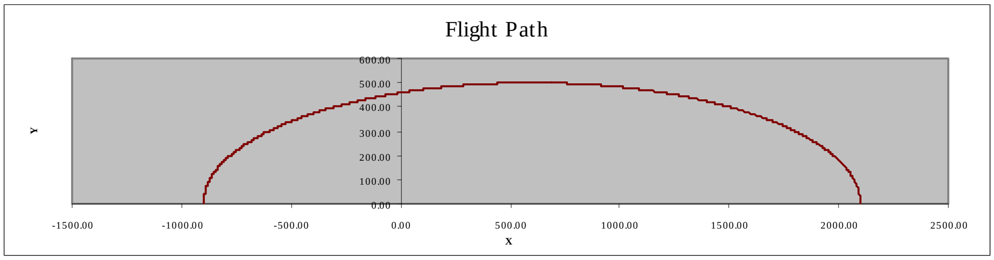
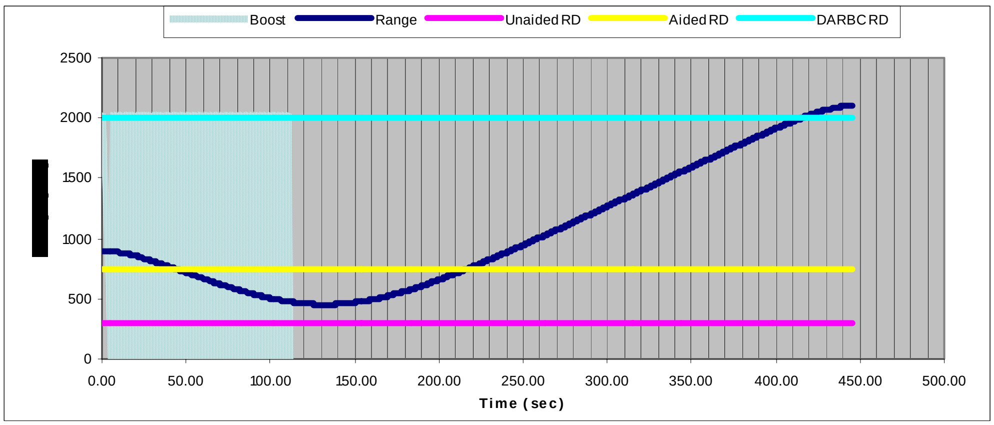
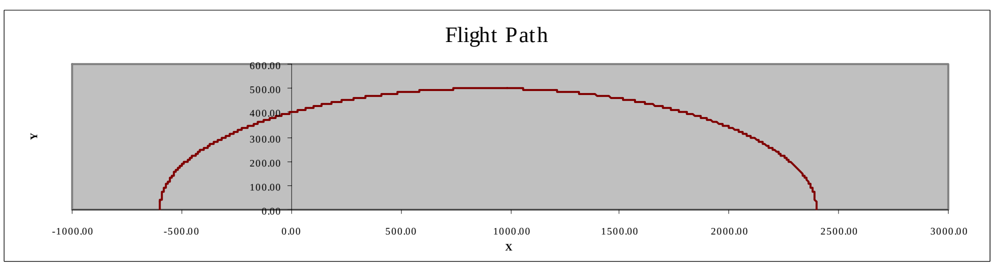
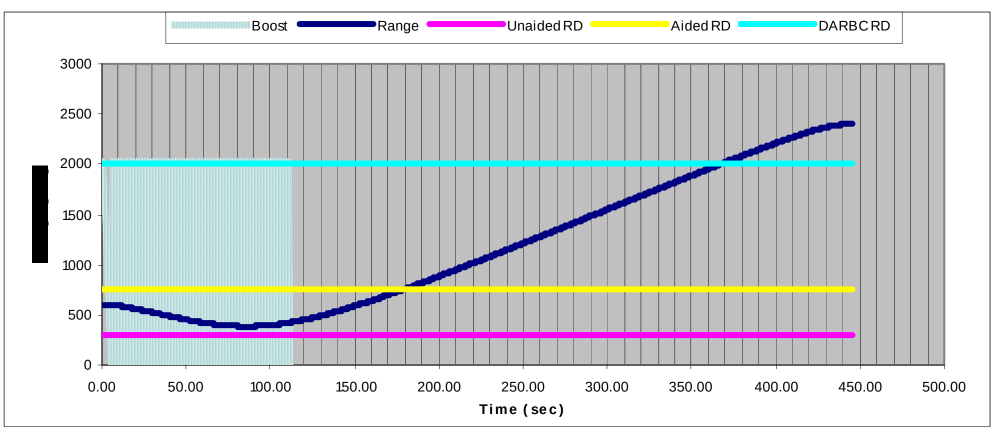
Launch Range	MRBM
900 km	
600 km	

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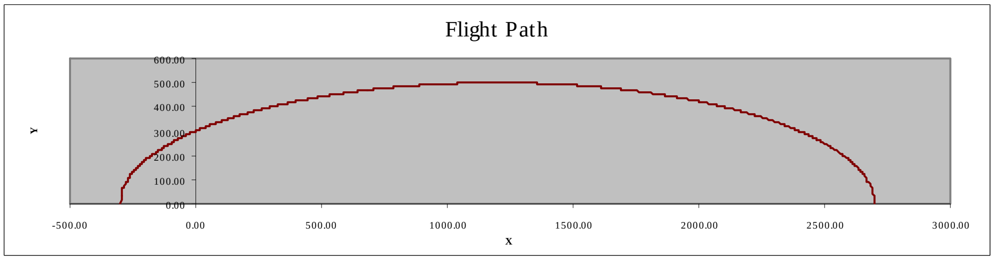
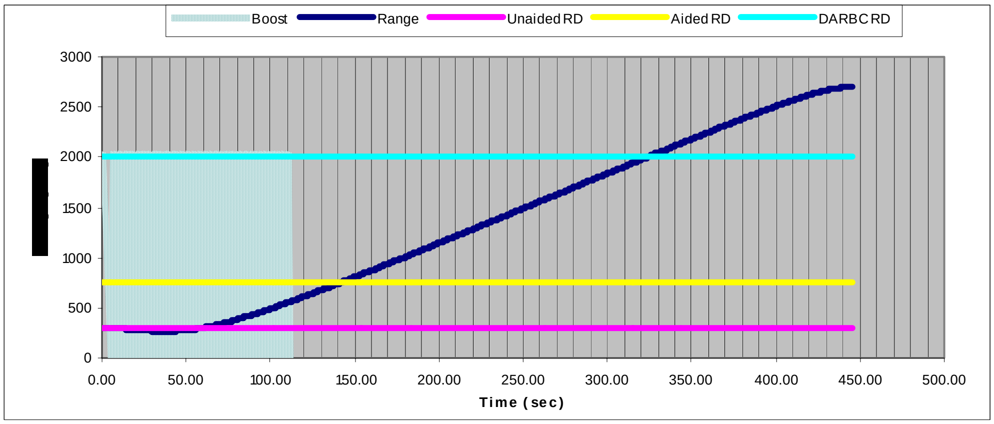
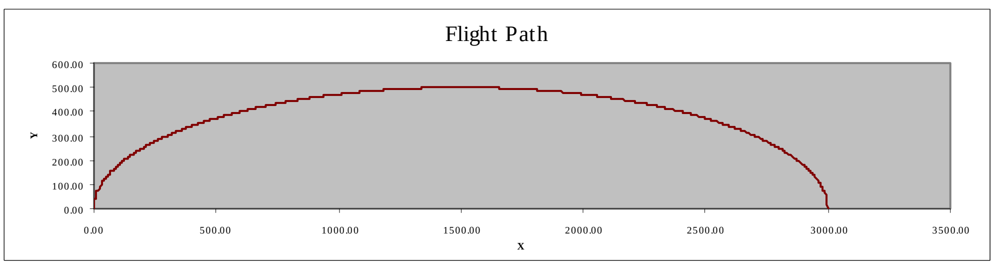
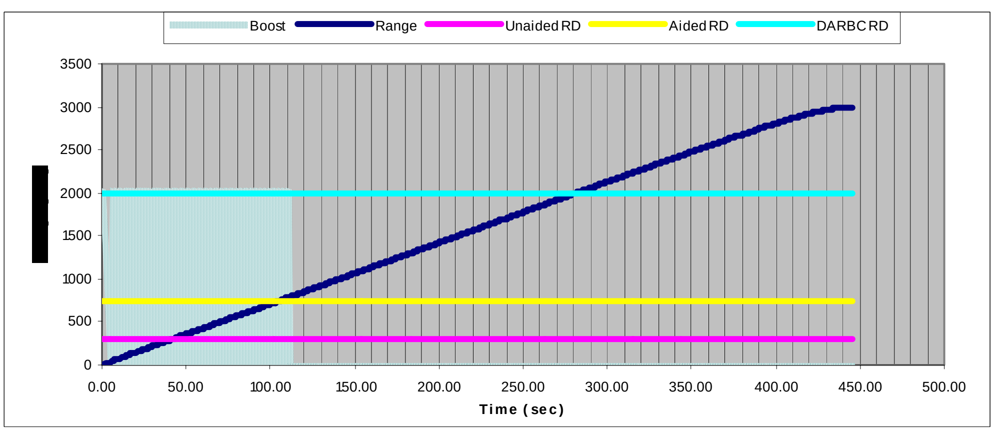




</td></tr>
<tr><td>0 km</td><td>




</td></tr>
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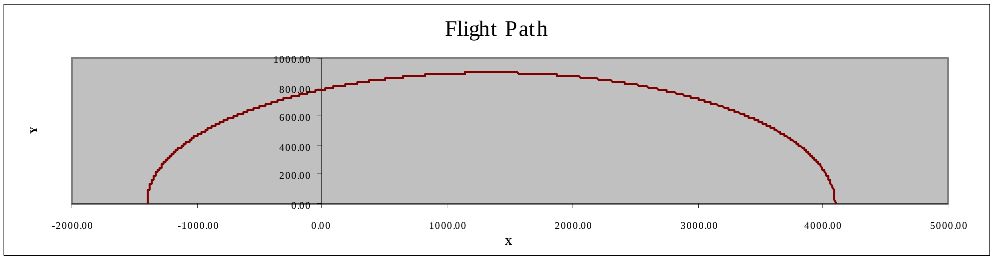
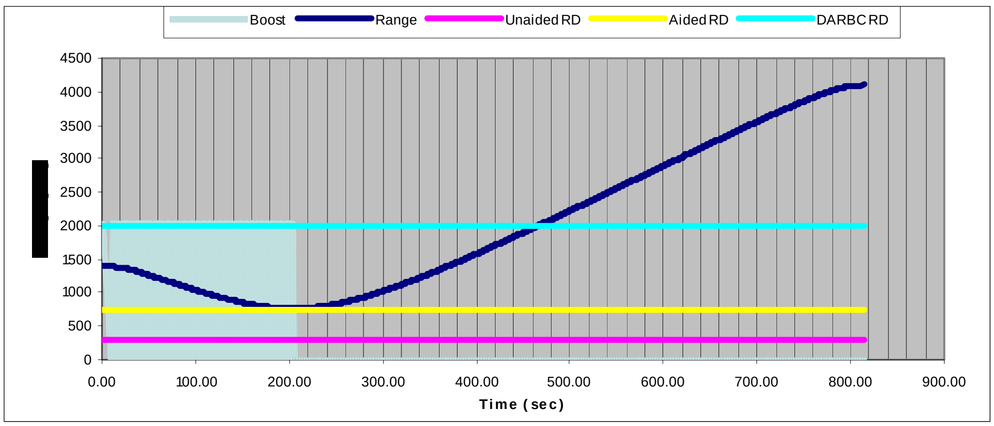
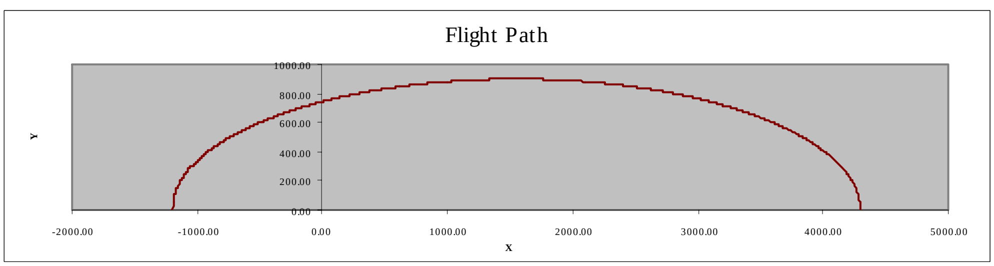
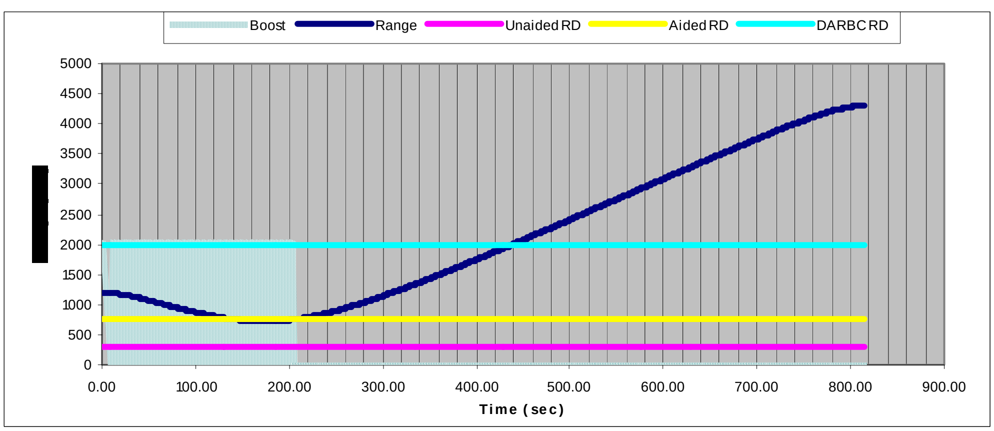
Table 7. IRBM Flight Paths and Time-Range Plots

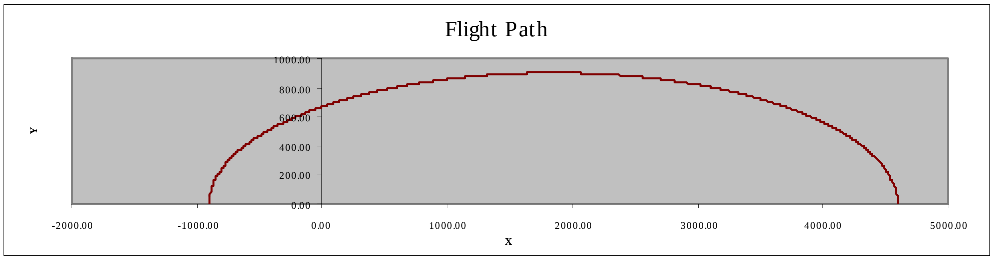
<table>
<tr><th>Launch Range</th><th>IRBM</th></tr>
<tr><td>1400 km</td><td>


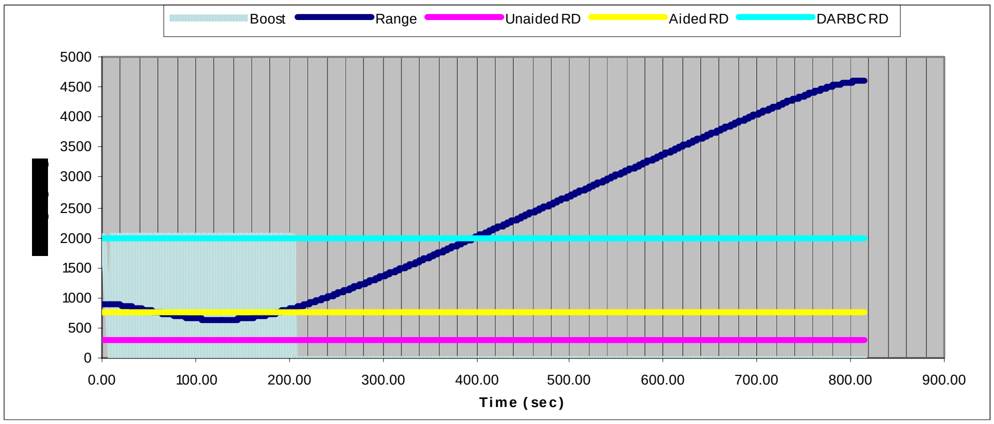


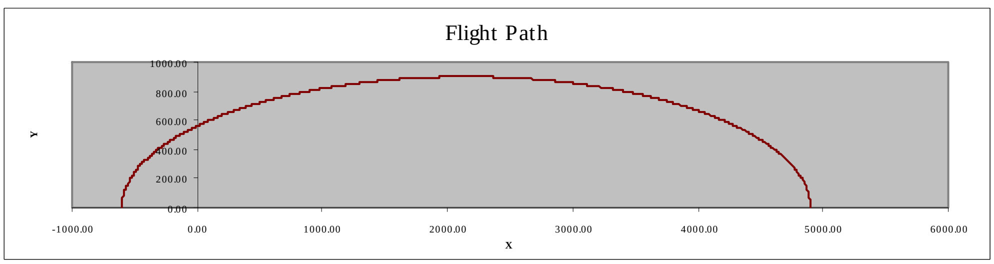
</td></tr>
<tr><td>1200 km</td><td>


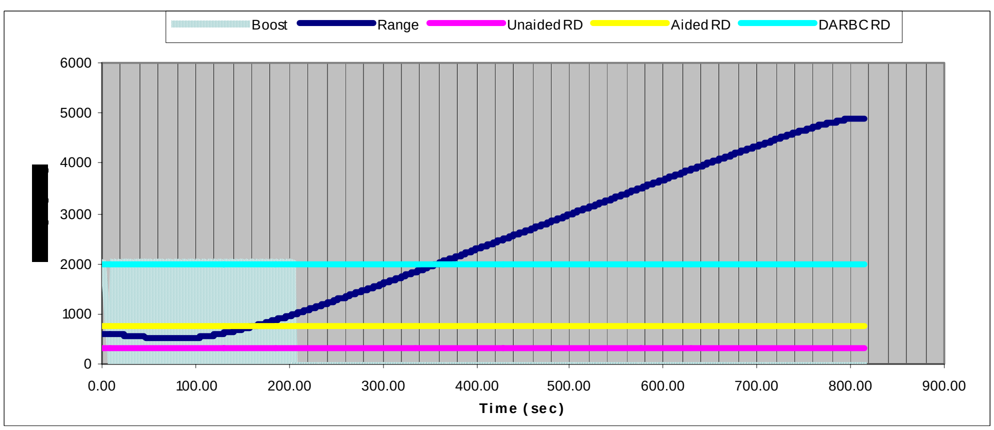


</td></tr>
</table>

<table>
<tr><th>Launch Range</th><th>IRBM</th></tr>
<tr><td>900 km</td><td>




</td></tr>
<tr><td>600 km</td><td>




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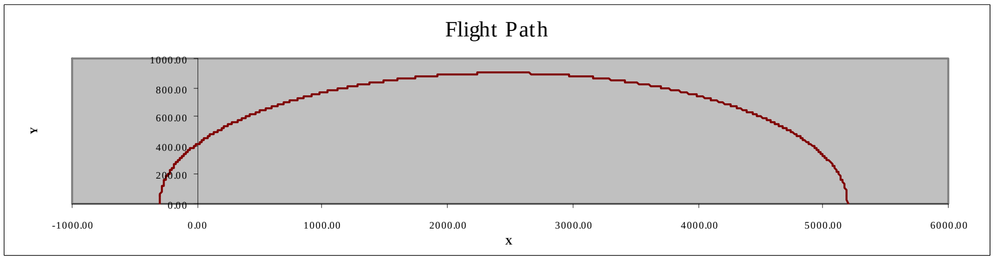
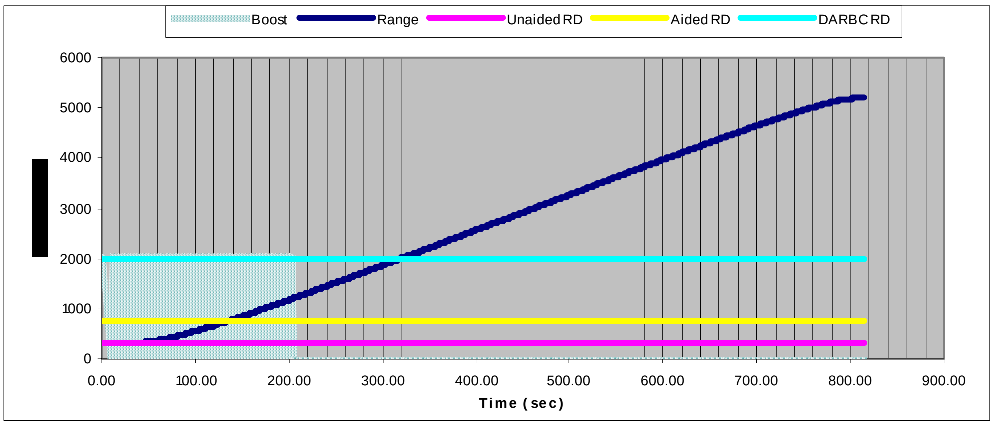
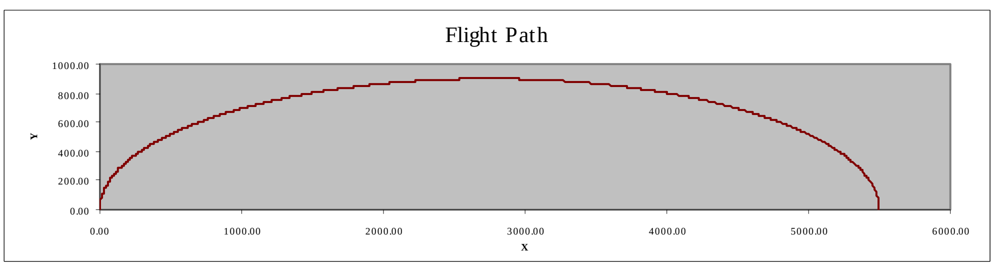
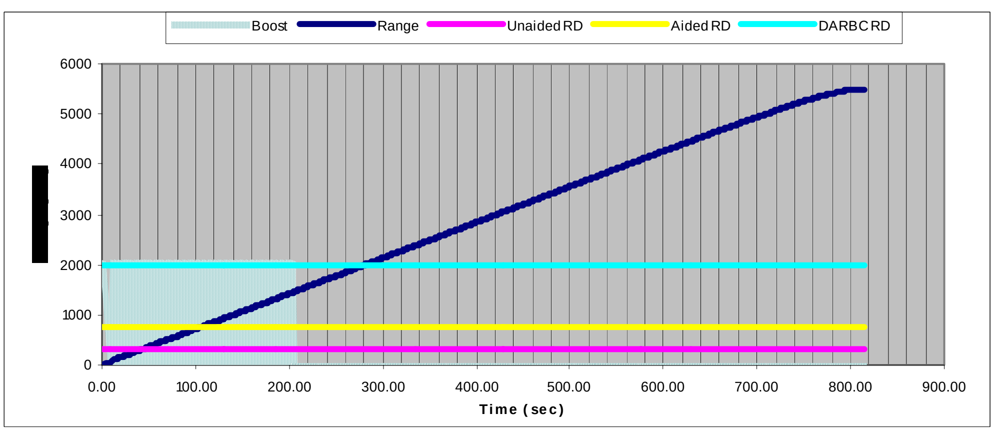
<table>
<tr><th>Launch Range</th><th>IRBM</th></tr>
<tr><td>300 km</td><td>




</td></tr>
<tr><td>0 km</td><td>




</td></tr>
</table>

Figure 32 through Figure 34 are based on further analysis of the time-range plots in Tables 8, 9, and 10. Each plot shows the times in each range-space stacked, i.e., showing the additional time presented by each range-space. The area under the Unaided-t line shows launch ranges that would be engagable by an isolated WCR and how long a target would be engagable. The area between the Unaided-t and the Aided-t lines shows the launch ranges that would be engagable by a WCR when cued by the DARBC and duration of that engagability. The area between the Aided-t and DARBC-t lines shows how much extra time would be available to evaluate a target with a given launch range. They also show improvement in the launch range coverage as the horizontal distance between the point before reaching zero on the Unaided-t line and the Aided-t line. They show information about a TBM launched at a range of 0 km. The span of launch ranges shown begins at 0 km and ends at the smallest launch range that presents 0 engagability time. The ends of the span are shown for continuity but are not meaningful and are not addressed in this analysis.

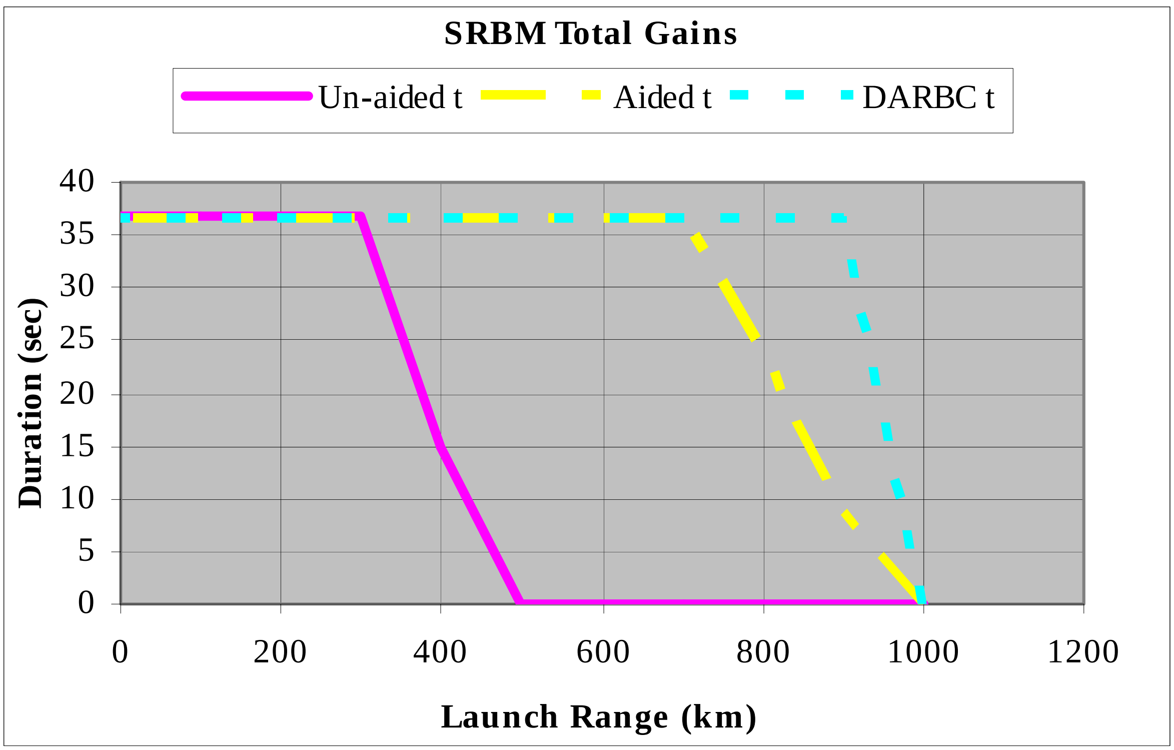


Figure 32. DARBC Gains for SRBM

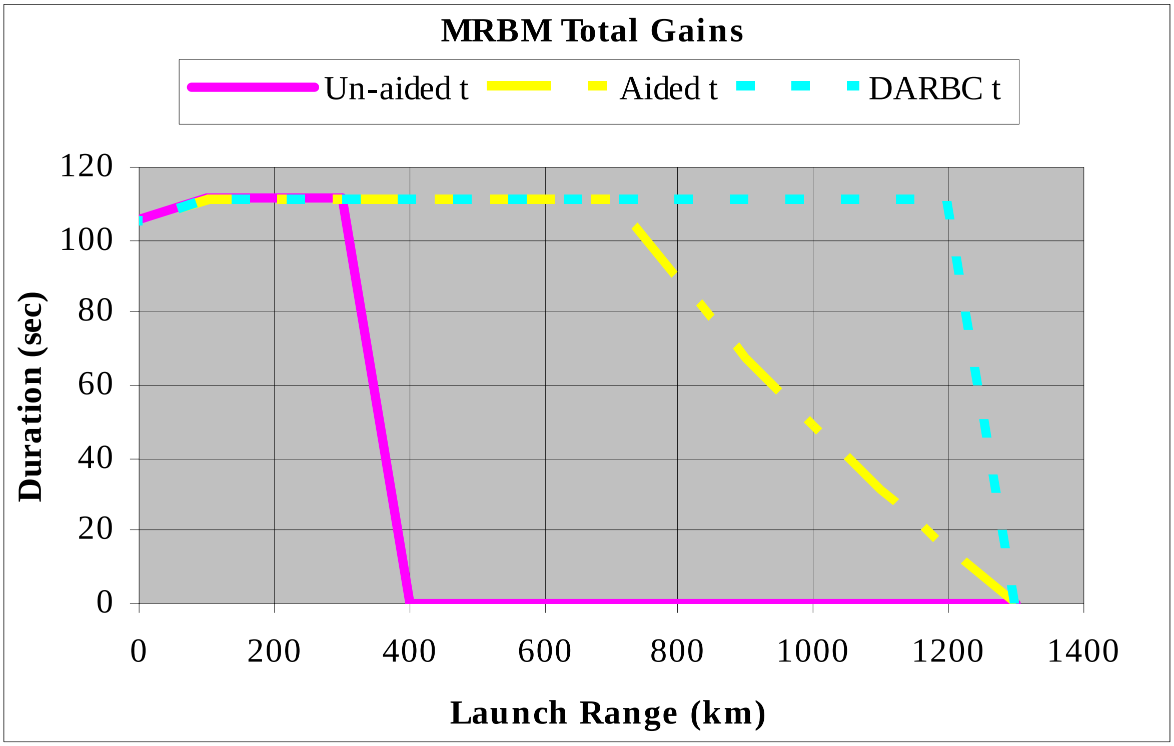


Figure 33. DARBC Gains for MRBM

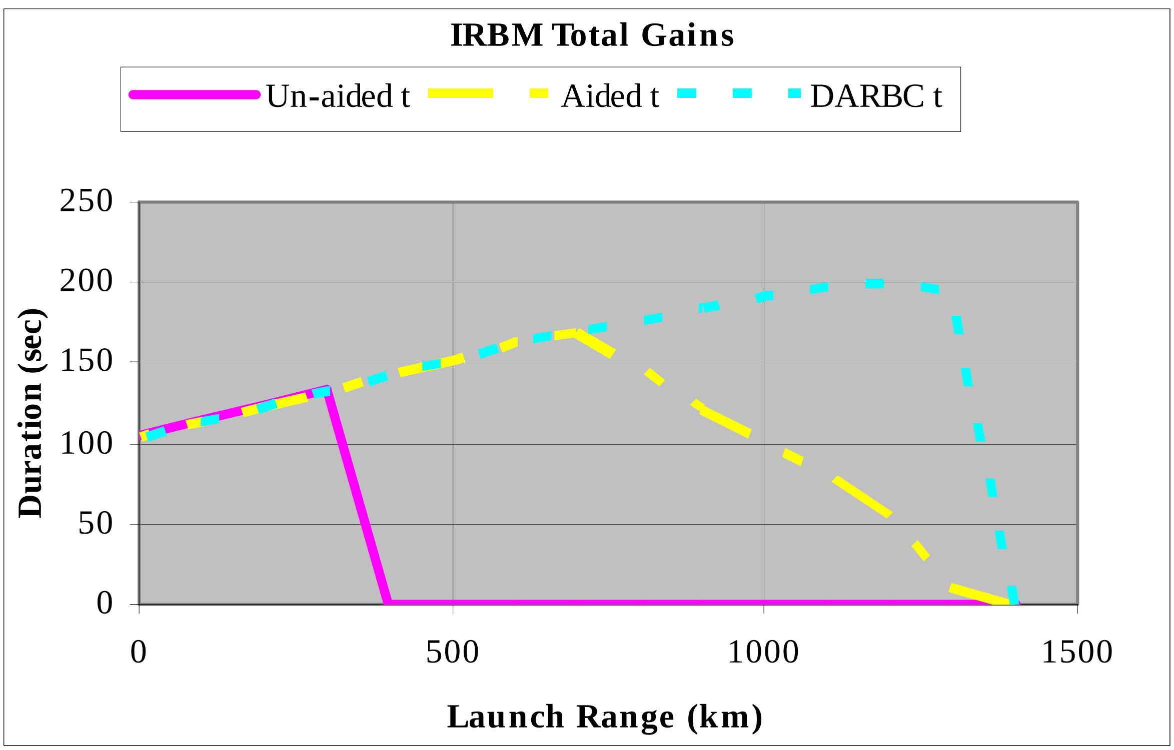


Figure 34. DARBC Gains for IRBM

IV. CONCLUSION

DARBC would provide the generic benefits of having an additional sensor available, increasing the overall Probability of Detection (P_D). That would allow the time resources of the WCR to be re-prioritized. Using only a handoff to an organic weapon system, the DARBC also shows the following benefits:

As shown in Figure 32, for the SRBM, the DARBC provides

- up to 22 seconds of additional engagement time at a launch range of 400 km,
- up to 28 seconds of additional evaluation time at a launch range of 900 km,
- increased coverage from 400 km to 900 km launch range.

As shown in

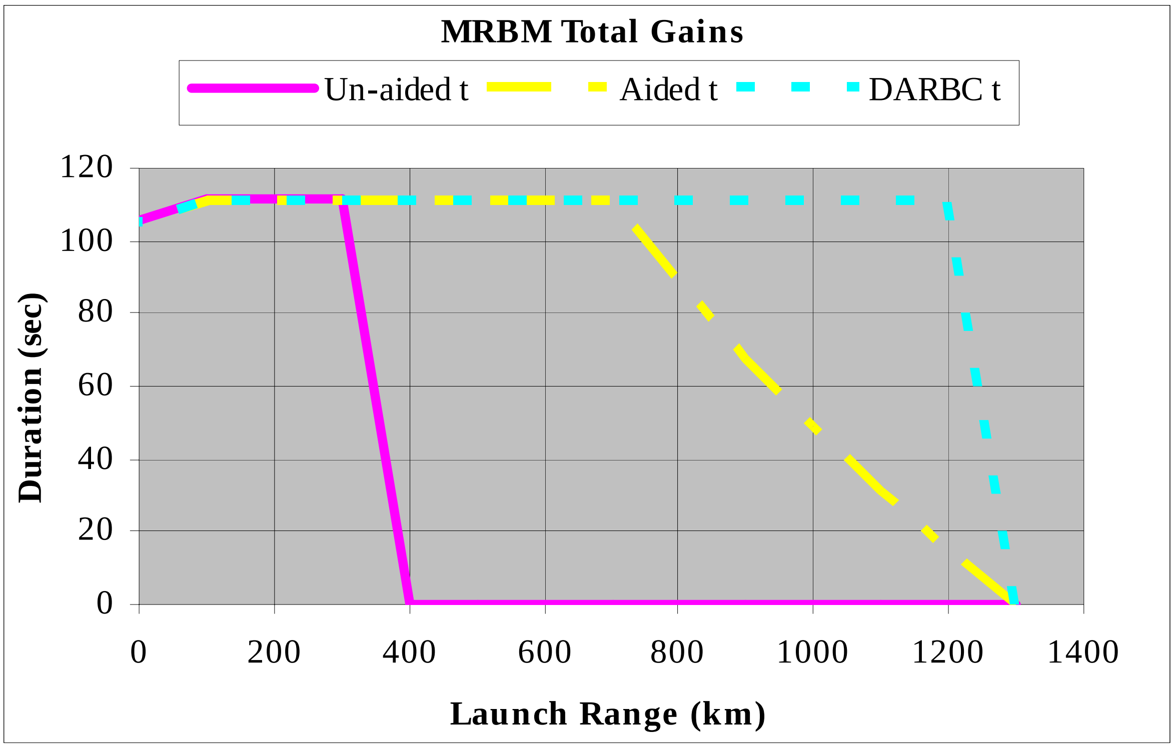


Figure 33, for the MRBM, the DARBC provides

- up to 96 seconds of additional evaluation time at a launch range of 1200 km
- increased coverage from 300 km to 1200 km launch range.

As shown in Figure 34, for the IRBM, the DARBC provides

- up to 182 seconds of additional evaluation time at a launch range of 1300 km
- increased coverage from 300 km to 1300 km launch range.

Model Used: C:\Documents and Settings\Paul\Deskto

F. DARBC-TN-07 APERSTRUCTURE HULL INTEGRATION

Document Type: Technical Note		**Document Number:** DARBC-TN-07
Program: DARBC		**Classification:** Unclassified

TITLE: Ship Topside Layout

PROBLEM STATEMENT:

A study on the location and number of Opportunistic Array (OA) Transmit/Receive (T/R) elements of the Digital Array Radar for Ballistic Missile Defense (BMD) and Counter Stealth (DARBC) system is needed in order to describe how the radar elements can interface with each other and operate on the skin of the hull. The proposed number of OA T/R elements on the ship's skin will help determine radar performance and limitations. The layout will then be configured with the Array Density requirements, radar equations, M&S, and cost.

Expected Outputs of Study:

Notional layout of array elements within the hull aperstructure

Ship topside integration parameters

Array Density Requirements

Prepared by: Ian Barford	**Original Date:** August 21, 2006	**Comments:** Submission of Final Technote
Reviewed by: Robert Hazle	**Date:** August 19, 2006	Reviewed
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** August 23, 2006	Reviewed
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

The purpose of this technote is to show how to integrate several hundred wireless Transmit/ Receive (T/R) module elements into the outside skin of a ship's hull. The elements will be arranged in clusters called "Arrays" and these arrays will be close enough to generate the needed radar envelope.

II. BACKGROUND

In order to have no interference between OA elements the minimum physical spacing between the elements on the hull of the ship has to be greater than ½ of the wavelength of the beam in use. Since the DARBC radar will operate in the UHF (216-225 MHz) and VHF (420-450 MHz) frequency bands the desired minimum spacing between elements (the spacing which will cause no interference) will be the shorter distance of ½ of the wavelength of each of the two frequencies. The current spacing between elements of one meter will cause no interference.

Furthermore, periodic array designs typically maximize the spacing between individual antenna elements yet keep it small enough to eliminate grating lobes. The condition for avoiding grating lobes under all conditions of beam-steering is:

$$d \leq \frac{\lambda}{2}$$

d = space between individual elements

λ = wavelength

Phased array radars are most commonly designed as periodic arrays. In developing the aperstructure concept, however, it is important to investigate if aperiodic arrays are able to achieve comparable performance. The reasoning is the ship's superstructure makes it physically unfeasible to implement a uniform, periodic array over the entire structure. In addition, integrating an array of closely spaced antenna elements across the entire structure is impractical and likely to be extremely costly[125].

III. DISCUSSION

Each element is a 0.5-meter square aperstructure that will be fitted into a circular (0.5 meter diameter) hole for minimum ship flexure[126]. The elements will be integrated into the ship as it is being built. The array faces will be flush with the surface of the hull and no protrusions will exist from the array or hardware to attach the array. This design is not intended for a backfit to any ship or hull design because of the extreme mechanical engineering difficulties of cutting hole into the side of a ship while trying to maintain its structural integrity. Figure 1 gives a visual of the starboard side of the proposed ship with the populated array faces. The array faces are situated to not interfere with existing hardware. The array faces are strategically located above the waterline tumblehome hull, and will not bump against the pier while ship is docked. No array faces are on any deck

of the ship so no one on the crew will be in the radiation path and the movement of stores and ordnance during replenishment will not damage to T/R elements.[127] Table 1 shows the proposed location of array faces. On the starboard side there is an array face that consists of 3411 array elements. On the port side, there is the same number of elements. Not pictured on the aft side of the ship, there is one array face that consists of 200 elements.

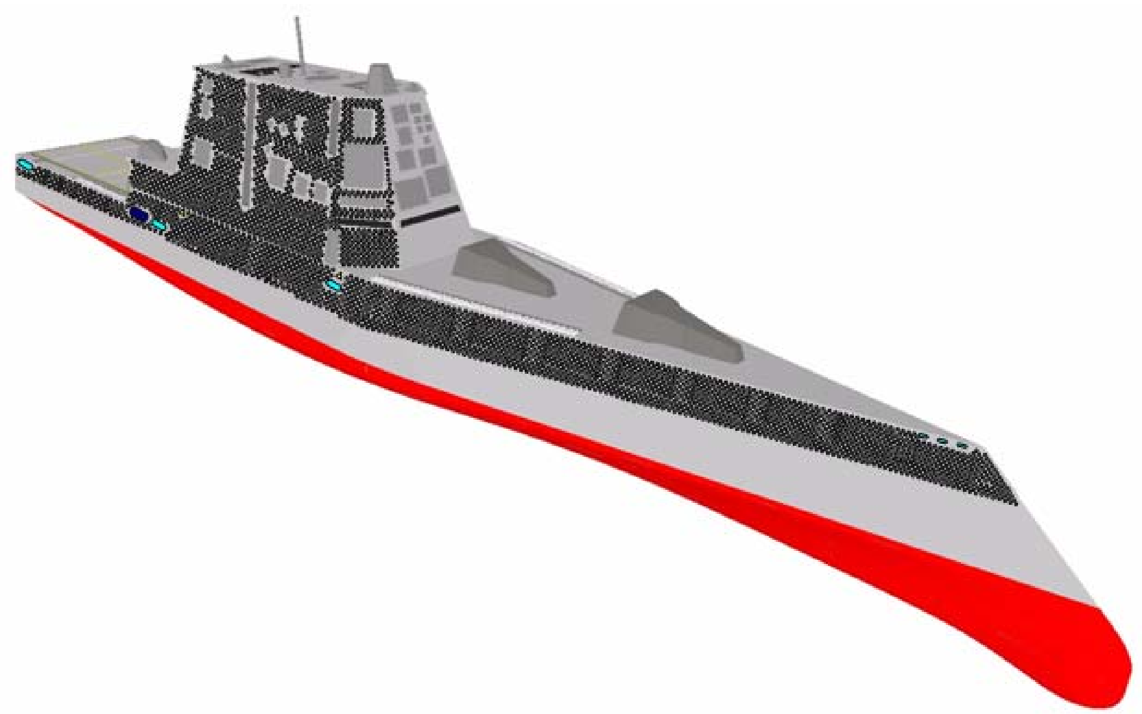


Figure 1 – Notional Placement of Array Faces on Starboard Side

Side of Ship	Number of Array Faces	Number of Elements per Array Face	Total Number of Elements
Starboard	1	3411	3411
Port	1	3411	3411
Aft	1	200	200
		TOTAL	***7022***

Table 1 – Number of Proposed Elements

Figure 2 is a pictorial view of the 95 elements that make up an array and shows the notional layout of each element with their spacing.[128] In 1 m^2, there are a total of 2 array elements (seen in the red box in Figure 2.

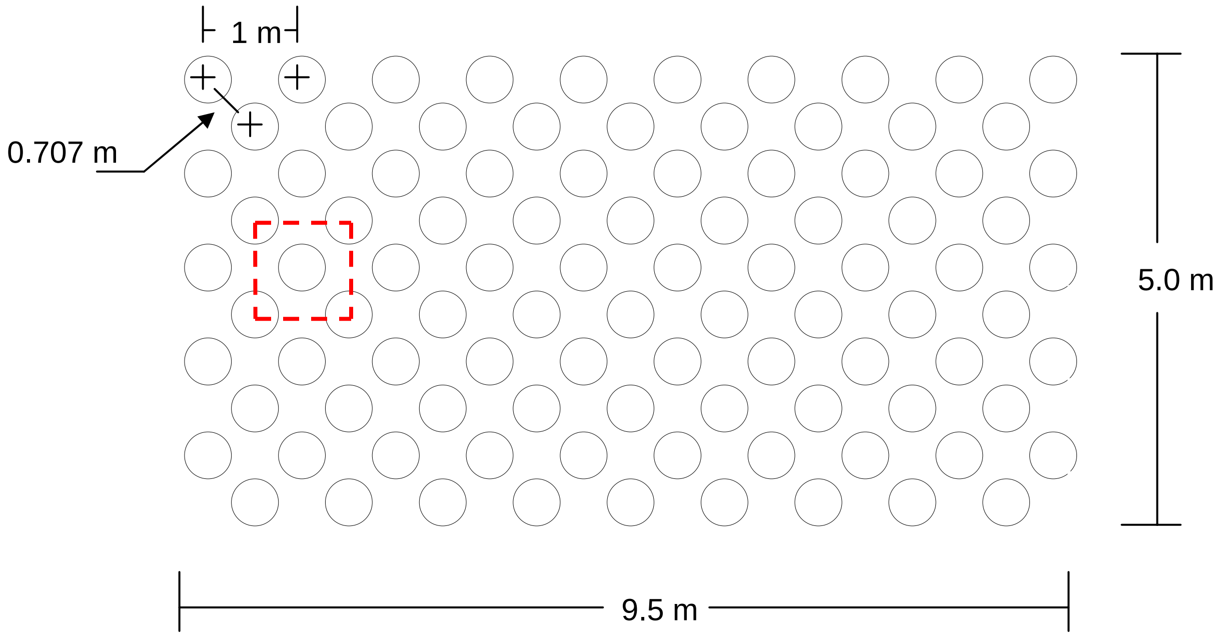


Figure 2 – Notional Placement of Elements within an Array Face

One of the inherent disadvantages to using this spacing between OA elements is the effect known as mutual coupling. Mutual coupling occurs between closely spaced antenna elements. Coupling may occur by radiation, from surface paths, from paths within the feed structure or from reflections at the antenna terminal due to impedance mismatches. The effects of mutual coupling include distortions in the radiation pattern and variations in the element gains. Mutual coupling may be characterized by a coupling coefficient c_{mn} that relates the current flowing into the nth element due to the current from the mth element. For isotropic elements, this coefficient is given as:

$$c_{mn} = \frac{\sin(kd_{mn})}{kd_{mn}}$$

d_{mn} = distance between nth and mth elements

K = coupling coefficient constant

Figure 3 below graphs the relationship between the mutual coupling coefficient and the separation between antenna elements. Observe that the equation for c_{mn} is simply a sin function. Hence, the effects of mutual coupling are undulatory with the distance between the elements and the envelope of the coupling coefficient decreasing with separation.

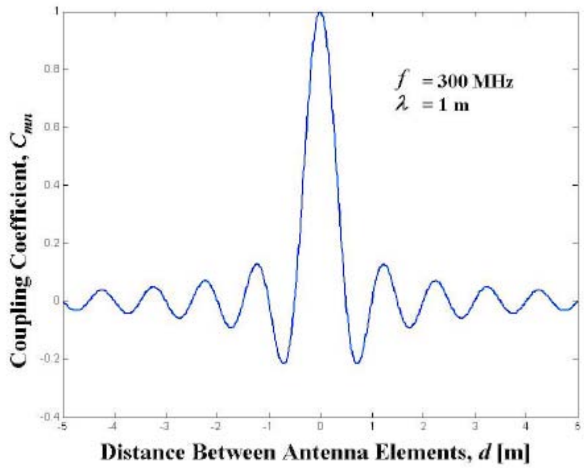


Figure 3 - Relationship between Coupling Coefficient and Antenna Element Separation

Theoretically, the effects of mutual coupling can be calculated and hence compensated. In reality, the coupling coefficient is not easily measured, is not stable with scan angle and is not conveniently controlled; especially for large ship-sized arrays which are too big to be tested in a controlled environment. The best way to reduce the effects of mutual coupling is to increase the distance between individual antenna elements beyond the requisite $\frac{\lambda}{2}$ criteria presented in the equation for c_{mn}. This process is commonly known as "thinning." This approach can possibly result in higher sidelobes and increased grating lobe levels unless an aperiodic array is designed.[129]

In order to have minimal interference between OASR elements, the minimum physical spacing between the elements on the hull of the ship should be greater than ½ of the wavelength of the beam in use. The DARBC radar will operate in the VHF (216-225 MHz) and UHF (420-450 MHz) frequency bands. Calculation of the wavelengths for the extreme ends of the radar's spectrum is seen below.

$$VHF\lambda_{\max} = \frac{299{,}792{,}458m}{s} \times \frac{1}{216 \times 10^6 Hz} = 1.3879m$$

$$VHF\lambda_{\min} = \frac{299{,}792{,}458m}{s} \times \frac{1}{225 \times 10^6 Hz} = 1.3324m$$

$$UHF\lambda_{\max} = \frac{299{,}792{,}458m}{s} \times \frac{1}{420 \times 10^6 Hz} = 0.7138m$$

$$UHF\lambda_{\min} = \frac{299{,}792{,}458m}{s} \times \frac{1}{450 \times 10^6 Hz} = 0.6662m$$

The desired minimum spacing between elements (the spacing which will cause minimal interference at any frequency of operation) will have to be ½ VHF λ (max) which is 0.695m. Our goal is to have this minimum separation between array elements in all directions within the aperstructure. This spacing will minimize phase interference between elements which plays a part in optimizing the DARBC's ability to have the narrowest beam possible. A one degree beam-width will translate to a 35 km beam width at a range of 2000 km so it is necessary to consider everything within the design of the radar which can influence the beam width. A narrower wavelength separation may cause the beam to have a large scatter point when it illuminates the target, thereby causing the convergent point of the beam to be off slightly.

IV. CONCLUSION

Table 2 shows the parameters for the ship topside integration.

Array Element Size	0.5 square meters x 2" thick
Feed Horn Size	0.0762 meters (diameter)
Calculated Element Spacing (Min)	0.695 meters
Proposed Element Spacing (Min)	0.707 meters
Number of Elements per Face (Min)	200 elements
Number of Elements per Face (Max)	3411 elements
Number of Array Faces	3 faces
Total Number of Elements	7022 elements (see Table 2 for explanation)
Average Power per Element	400 Watts
Maximum Power	2.80 Mega Watts
Weight of Each Element	10 lbs
Total Weight of Elements	70,220 lbs

Table 2 – Ship Integration Parameters

Maximum power is based on 100% of T/R elements transmitting to port or starboard (3411 elements). Operationally it would be anticipated that less than 100% of the elements would be used and performance characterization may be based on a different value for Power.

G. DARBC-TN-08 SHIP FLEXURE

Document Type: Technical Note		**Document Number:** DARBC-TN-08
Program: DARBC		**Classification:** Unclassified

TITLE: DARBC Ship Flexure Impacts

PROBLEM STATEMENT:

The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) has radar Transmit/Receive (T/R) elements dispersed throughout the ship hull and superstructure. Ships are subject to flexure due to a variety of construction, environmental and operational parameters. Ship flexure will have an impact the alignment of these T/R elements and resulting radar performance. This impact needs to be understood and determination if compensation needs to be provided.

Expected output of Technote:

This Technote will describe and classify ship flexure error sources and summarize an error budget. It will provide a discussion of dynamic compensation methods to reduce flexure errors.

Prepared by: Bob Hazle	**Original Date:** 13 August, 2006	**Comments:** Rev 19 Aug, 2006
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Ian Barford	**Date:** 17 August, 2006	Comments given
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 19 August, 2006	Final review of Technote
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

Ships are subject to flexure due to a variety of construction, environmental and operational parameters. The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) has radar Transmit/Receive (T/R) elements dispersed throughout the ship hull and superstructure. Ship flexure can impact system performance by introducing alignment errors between elements. Traditionally these errors occur between various elements such as a fire control radar and a gun system. For the DARBC, errors introduced by ship flexure will be across T/R elements which will affect beam forming and antenna alignment. This can impact radar system performance for detection of threats and in providing accurate track information for handover to other sensors in the Ballistic Missile Defense (BMD) system network. Current systems performance has not suffered as error budgets absorb ship flexure errors. Increasing ranges and capabilities of ballistic missile threats and resulting system capability requirements may not allow this in future systems like DARBC.[130] This paper attempts to identify errors and classify in a system error budget. This paper will also describe potential methods for compensation.

II. BACKGROUND

Ships need to flex to prevent intolerable buildup of stresses in the ship structure when subjected to operational conditions of the sea.[131] Ship flexure shows up as relative rotational motion between two points and can result in unfavorable misalignment between elements located between these two points. In traditional (current) combat system configurations this results in static or bias errors and dynamic errors between various combat system elements. These errors have been calculated and handled through system error budgets as opposed to providing a compensation to eliminate or reduce these errors. Despite being the largest error contributor, ship flexure is deemed acceptable as its impact is reduced by systems with closed loop tracking, large beamwidths of illuminators, and close in engagements (relative to ballistic missile engagements). As engagements increase in range from ship to meet increasingly capable threats, these errors can become intolerable to support functions such as handover to sensors (organic and off platform) and engagements with missile or other weapon systems. DARBC is a non traditional sensor. As the array elements are distributed across the ship hull and superstructure, ship flexure will have a significant impact on element to element positional spacing and alignment resulting in phase differences of T/R element impacting overall system performance.

III. DISCUSSION

Ship flexure is generally defined as the uncompensated relative angular difference between two combat system elements from the compensated aligned state. Combat system alignment is accomplished on every ship to baseline the system. This is accomplished as part of new construction and after major overall maintenance periods. Additionally alignments can be done throughout the life cycle of a ship when it is believed an error exists. Alignment is a very time consuming and labor intensive process which can be interpreted as costly and therefore undesirable to perform. Combat system

alignment is performed pier side during the night or morning hours before solar heating can impact measurements. Flexure is broken down into static bias errors which occur over a long periods (minutes to permanent) and dynamic which is constantly changing during an engagement.

Static Flexure Examples:

1. Solar loading. The sun can dramatically impact ship flexure. If the sun is exposed to only one side of the ship as in morning or evening hours it will heat the ship and cause expansion relative to the unexposed side. Solar loading can create changes of several arc minutes between elements. The amount of solar loading and shade, material of the ship and its expansion under heating, duration of loading all contribute to amount of change.
2. Lead-out. Ships require a great deal of material for operation including weapons, fuel, food stores, spares, personnel and associated materials. This distributed weight varies as the ship operates (consumes fuel and other material). Alignment of ships is generally conducted when ships are loaded to 90% total weight. This requirement can be difficult to achieve as the ship may not be fully equipped at the point of alignment. Loading arrangement during alignment test may also not reflect operational lead-out as weapons and material may need to be simulated.
3. Temperature. Similar to solar loading, air and sea temperature can have dramatic effects on ship alignment by expansion of hull materials.
4. Impact. A permanent flex or bend to a ship caused by a load such as a large swell, impact with another ship or pier, near explosion. When detected this can be measured through another alignment test and compensated for.
5. Steady winds.
6. Improper measurements during alignment test. Human error, test equipment error and poor procedures can contribute to a static error problem by not properly measuring baseline alignment of a ship.

Dynamic Flexure Examples:

1. Waves. Sea state is the most common parameter describing the load that forces ship flexure. Sea state is a standard measure of wind speed, swell size and swell period that can cause hogging and twisting moments on the ship. The length and beam of the ship, its speed and direction relative to the seas as well as its height and construction material and structure will ultimately determine susceptibility to flexure under load. A large swell of a period that introduces the most significant hogging effects is considered the worst condition.
2. Vibration. Vibration on a ship can be causes by a number of sources such as operating equipment and operational environment induced by sea state.
3. Maneuvers. Speed and rate of turns will cause torsional loads on ship hull.

Flexure Impact to Alignment and Radar Performance:

Susceptibility to flexure can vary across ship class designs due to a variety of impacts. Ship design aspects such as material (Steel, aluminum, composite), construction (material thickness, support structure, open space), length, beam, weight, height, hull type

(mono-hull, catamaran, trimaran other) all contribute to the stiffness or flexibility of the ship overall or in certain locations. The further away from amidships on the hull a superstructure element is located, the greater the susceptibility to flexure can be expected. Also the farther up the mast an element is located the greater flexure can impact. The use of aperstructures needs to be considered due to the use of composites which may have different response to flexure than metal hulls. No analysis is provided in this Technote as to whether this would have a positive or negative effect. The large dispersal of elements along the hull can contribute to effect of alignment. Alignment errors will have the following two primary impacts which are depicted in figure 1:

- T/R elements will be out of relative position resulting in phase shift errors, decreasing antenna gain and reducing performance for detection and tracking.
- Antenna alignment to ships reference will be effected causing bias errors resulting in mismatch between antenna and other sensors and possibly sections of the antenna. This could result in lost tracks and poor handover between elements.

Dynamic flexure is usually a cyclic event and can be minimized by mathematical filters in the radar. Static flexure is an unknown bias and cannot be undone with filtering. Reference (a) discusses criteria for sensor synchronization in detail and provides overall azimuth and elevation pointing error as ship does not act as a point source (gun, single phased array face, dish radar). This can be on the order of several milliradians. At 1000km, 1 milliradian error equates to a distance of approximately 300 meters. When different portions of the ship array elements provide the radiating portion of the radar, misalignment can occur as the track is handed over to other portions of the ship array elements due to ship turns and target relative position.

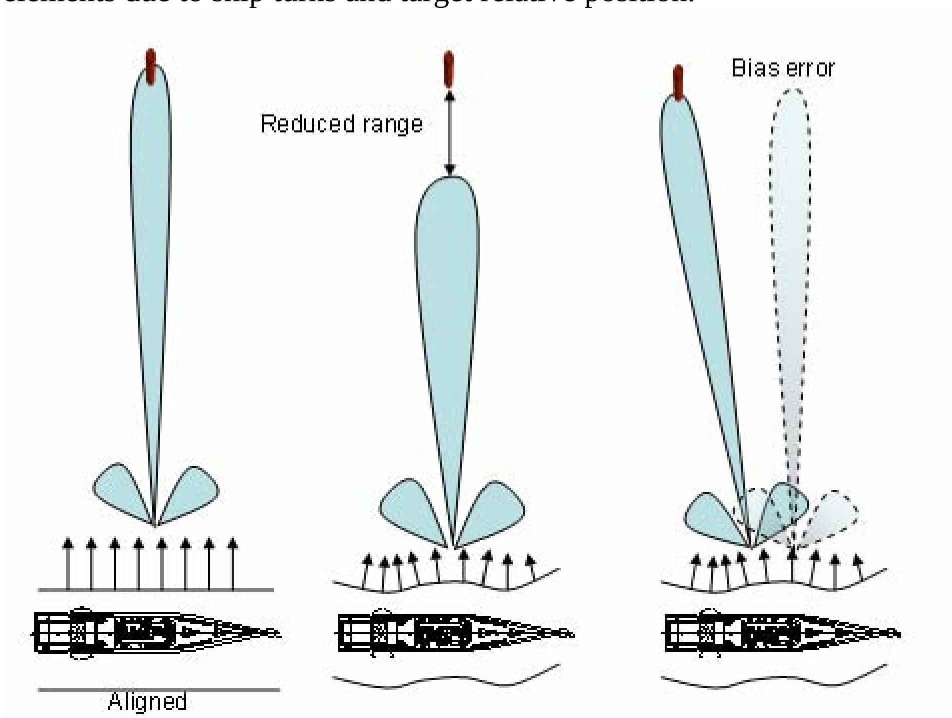


Figure 1. Ship flexure impact to beam formation and detection range reduction

Ballistic Missile Defense Problem:

The operating ranges for detection, tracking and engagement of ballistic missiles coupled with the small radar cross section of threats, high velocity of both threat and interceptor and need to hit-to-kill engagements allow for little error. Crossing targets make the intercept volume for a kinetic kill weapon smaller. The intercept volume is the space that the target and weapon will fill at the same time. A nose on engagement can provide a longer volume as intercept timing will be dependant on the angle of attack. Figure 2 shows this aspect angle effect for a straight on and crossing target case. Handover between sensors on the same platform is difficult due to time synchronization errors of the two systems in addition to alignment errors. On a single platform the sensors are generally aligned to the same reference point and use the same geodesic reference. They can also be keyed to the same clock reference. Handover to a second sensor separated from the ship will increase potential for time synchronization errors and positional reference problems. Sensors can be cued and depending on the particular sensor beamwidth capability, can be directed into a search pattern to acquire the target if errors are to significant where direct cueing will not generate a track.

If the sensor handover is to an interceptor, the error budget will be determined by the onboard sensor range and resultant phase of flight. This is generally late in flight and results in a very small error budget contribution. If the handover for DARBC is to a fire control level quality/accuracy sensor, the error budget can be larger but will depend on the characteristics/performance of that sensor (or multiple sensors in the case of a network of BMD sensors).

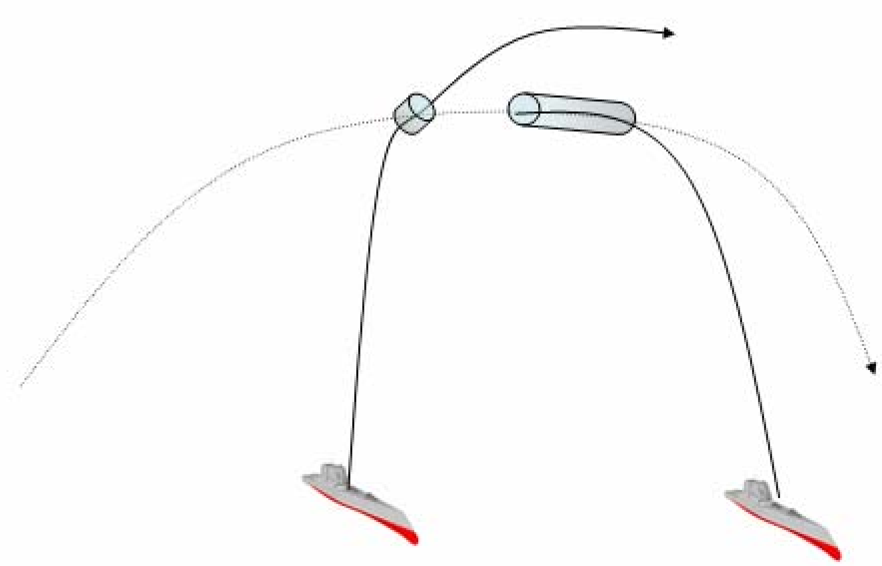


Figure 2. Two cases of head on and crossing aspect angles

Antenna Alignment of DARBC array

Large antenna arrays such as DARBC will naturally flex over time and require a cohering or calibration method to determine antenna element locations and provide accurate digital beam-forming. Reference b. provides a description of a broadcast reference technique that could be applied for the DARBC. The method measures phase of each element with respect to a number of reference beacons. Reference (b) also describes a self-cohering technique where one element (or possibly more) transmits conducting a self survey of the array which also applies the use of reference beacons. The uses of beacons in both the far field and near field are implied in the article.

Cost and time to perform a physical measurement and mechanical battery alignment of approximately 2000 elements of an Opportunistic Array (OA) would be time and cost prohibitive. The capability to dynamically calibrate, while in port or on a fixed site will be required for this radar system. The use of reference beacons of known location with respect to the DARBC ship would potentially require the development of special facilities. The entire radar would need to be visible to the beacons which may not be practical in most navy ports. The ship would need to have the ability to transmit at this facility as well which can also be a problem especially at high power levels. A fixed or portable calibration system nearby Navy ports to be used upon exiting port is an option but would require the ship to be underway and subject to flexure effects from the sea. This calibration system would still be subject to the errors that can occur in alignment tests of today. Ship flexure due to solar loading, wind loading, and temperature variations would have the same impacts. Alignment of DARBC to other sensors would also need to be considered. The beacon array would ostensibly operate in the VHF/UHF band. Co-locating other frequency systems and optical reference objects could allow alignment to other primary sensors. The Shipboard Electronic Systems Evaluation Facility (SESEF) utilizes the Universal Radar Moving Target Transponder (URMTT) as a supplement to aircraft services and other Electronic Target Generators (ETG) also exist which could be used as a repeatable test tool to train ships and to help with alignment. Since SESEF facilities are land based, they are limited in assessing elevation. Placement of ETGs such as URMTT in an aircraft would allow elevation to be assessed.

Dynamic Compensation

Once aligned, dynamic compensation could be provided by a number of different means. Automatic laser tracking tools exist that can measure positions of targets in 3D coordinates with high accuracy. Ships that flex can use a number of laser elements and reflectors on the hull (the targets) to measure flexure dynamically. The system would need sufficient laser systems in certain portions of the hull form and algorithms and processing to determine though extrapolation flexure over large sections of the hull.

The use of differential GPS has been speculated and eliminated as an option for measuring positions of sensors under reference (a) Miniature Ring laser gyros could be

located throughout the ship to measure 3-dimensional rotation and compare to a reference plane to determine areas of flexure. Currently ships have two gyros for redundancy to measure ships roll pitch and yaw. The two gyros will show different responses while ship is underway and responses are recorded. This difference is due to ship flexure, differences in hardware alignment or drift of electronics internal to the gyros. This fact could permit multiple gyros to be placed around key positions on the ship that represent portions of array elements.

Reference (a) identified the potential use of Quartz Rate Sensor to detect angular rate motions. By integrating three gyros for three axis and coupling with a clock, angular displacement can be determined similar to the gyro concept described above. They have the advantage of being small and low cost but were deemed to immature in design at this point to be a viable alternative.

For all these options integration of these sensors for measuring flexure would require development of both hardware and computer software. Installation of small low cost sensor cages at key appropriate combat system elements including DARBC array elements would be required. The software would need to collect, correlate and interpret the data from the sensors and translate into dynamic compensation adjustments.

Gyros are likely to experience gyro drift over time. One possible way to minimize drift would be to develop a hybrid system consisting of both gyros and lasers. The lasers could be used to measure and periodically remove any bias.

Error Budget Elements	**Rough Order of Magnitude Change** RSS= root sum squared	**Rough Order of Magnitude Alignment Error (milliradians)**
Flexure Static	RSS	**39**
Temperature/sun	.5 m displacement	30
Wind loading	.3 m displacement	20
Load-out	.2 m displacement	10
Alignment test errors	n/a	5
Post alignment impact	.2 m displacement	10
Flexure Dynamic	RSS	**32**
Waves/maneuvers	.5 m displacement	30
Vibration	.2 m displacement	10
Time latency between sensors	RSS	**45**
DARBC to own ship sensor	negligible	0
DARBC to off ship Fire Control sensor	> .01 sec	45
DARBC as FC to interceptor missile		n/a
Geo Position error	RSS	**50**
DARBC ship to off board sensor	> 1 m displacement	50
Total Errors		**98**

Table 1 – Error Budget Ship Flexure

IV. CONCLUSION

The operational requirements for DARBC will provide determination of overall mission requirements and capabilities. The DARBC ship and its outfitted systems and interfaced systems to DARBC, will determine the error budget and define the capabilities the radar will be designed to. If ship flexure is determined to be too large of an error contributor, dynamic compensation will be looked at to reduce errors. Ship flexure errors may be exceeded by time latencies between platforms and position determination but will still be a significant contributor to overall error. The increased ranges and strenuous mission profiles to support BMD scenarios will likely cause tighter error budgets than today systems. The length and distribution of DARBC array elements will make this radar susceptible to flexure problems. Reduced detection ranges and difficulty in maintaining track or handing over to other sensors are the likely problems caused by this flexure. No methods exist today to measure and compensate for flexure. Several technologies have potential to provide dynamic compensation but none appear to be a clear leader. Further investigation of mitigating methods is recommended. Calibrating the DARBC array will likely need to be done both pier side and underway to verify alignment and determine compensation to remove biases. This calibration may be intensive for facility development due to expected unique configuration of ship and need to keep the process non labor intensive.

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DARBC-TN-10 ELEMENT COOLING

Document Type: Technical Note		**Document Number:** DARBC-TN-10
Program: DARBC		**Classification:** Unclassified

TITLE: T/R Module Cooling Requirements

PROBLEM STATEMENT:

The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter Stealth (DARBC) system will require a cooling system due to the high levels of power emitted by its subcomponents. This Technote will address cooling of the major concern for this system; the subcomponent Transmit/Receive (T/R) module. An assessment of the T/R module and its subcomponents is required in order to determine the best methods of cooling. This study is necessary to ensure cooling requirements for substrates are considered in the development of the T/R module for this Radar system.

Expected Outputs of study: List of T/R module components and possible substrates**,** Listing of potential T/R module cooling methods**,** Trade off impacts that could require future studies.

Prepared by: Jack Chung	**Original Date:** 8 April, 2006	**Comments:** Initial Submission of document
Prepared by: Bob Hazle	**Original Date:** 4 May 2006	11 August 2006 2nd pass, final review 8/19/06
Prepared by: Jack Chung	**Original Date:** 10 Aug 2006	
Prepared by: Jack Chung	**Original Date:** 12 Aug 2006	New Update
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Ian Barford	**Date:** 14 Aug 2006	Review conducted
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 19 Aug 2006	Final Review
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

This paper lists the cooling requirements for the key component of the DARBC Radar System, its T/R module. Different methods of cooling and their tradeoffs are considered in order to satisfy a range of requirements.

II. BACKGROUND

Reference (a) provided the thresholds for different types of substrate options that the T/R module may utilize. The substrate consists of a dielectric material that affects the electrical performance of the antenna, circuits and transmission line for OASR. References (b) and (c) provide information on the best method to cool the T/R module.

III. DISCUSSION

No initial attempt was made to define measures, thresholds or objectives. Requirements were identified from references (a). Table 1 compares various substrate options with relevant properties. The substrate properties include the different constant dielectric, loss tangent, dimensional stability, chemical resistance, and temperature range. In addition, the relative cost is also considered as part of tradeoff studies.

Table 1

Substrate	Constant Dielectric	Loss Tangent	Dimensional Stability	Chemical Resistance	Temperature Range (F degree)	Relative Cost
Ceramic Substrates						
Alumina	9.8	0.0004	Excellent	Excellent	to +1600	Medium to high
Sapphire	9.4, 1.6	0.0001	Excellent	Excellent	-24 to +370	Very high
Semiconductor Substrates						
GaAs	13	0.0006	Excellent	Excellent	-55 to +260	Very High
Silicon	11.9	0.0004	Excellent	Excellent	-55 to +260	High
Ferromagnetic Substrates						
Ferrite	9.0 to 16	0.001	Excellent	Excellent	-24 to +370	Medium
Synthetic Substrates						
PTFE (Teflon)	2.1	0.0004	Poor	Excellent	-27 to +260	Medium
Polypropylene	2.18	0.0003	Poor	Good	-27 to +200	Medium
Composite Material Substrates						
PTFE-glass, woven web	2.17 to 2.55	0.0009 – 0.0022	Excellent	Excellent	-27 to +260	Medium

T/R Module Component Analysis

Table 2 is a list of components from reference (d), that can be use to build the T/R module and the substrates that can be used for the component based on the new hybrid MIC/MMIC (microwave integrated) architecture:

Table 2

T/R Module		
Component	**Substrate**	**Function Area**
Bipolar Transistor	Silicon based	Transmit
Pin Diode	Silicon based	Receive
Low noise amplifier (LNA)	GaAs MMICs	Transmit
Digital Attenuator	GaAs MMICs	Receive
Phase Shifter	GaAs MMICs	Receive
T/R switches	GaAs MMICs	Transmit/Receive
Microstrip circuitry	Ceramic microwave laminates	Transmit/Receive

Analysis of Table 1 and Table 2 indicated that Temperature range for the Semiconductor Substrates range from -55 degrees to +260 F degrees and ceramic up to 1600 F degrees. These substrate materials provide excellent dimensional stability and chemical resistance.

Cooling Method

The research found that there are many different methods for transferring heat. These methods can be use for T/R module cooling. The optimal method depends upon the temperatures and tolerances of the application, and impact to system overall performance and supportability. Table 3 is an overview of other cooling techniques and their advantages and disadvantages from reference (b) and reference (c):

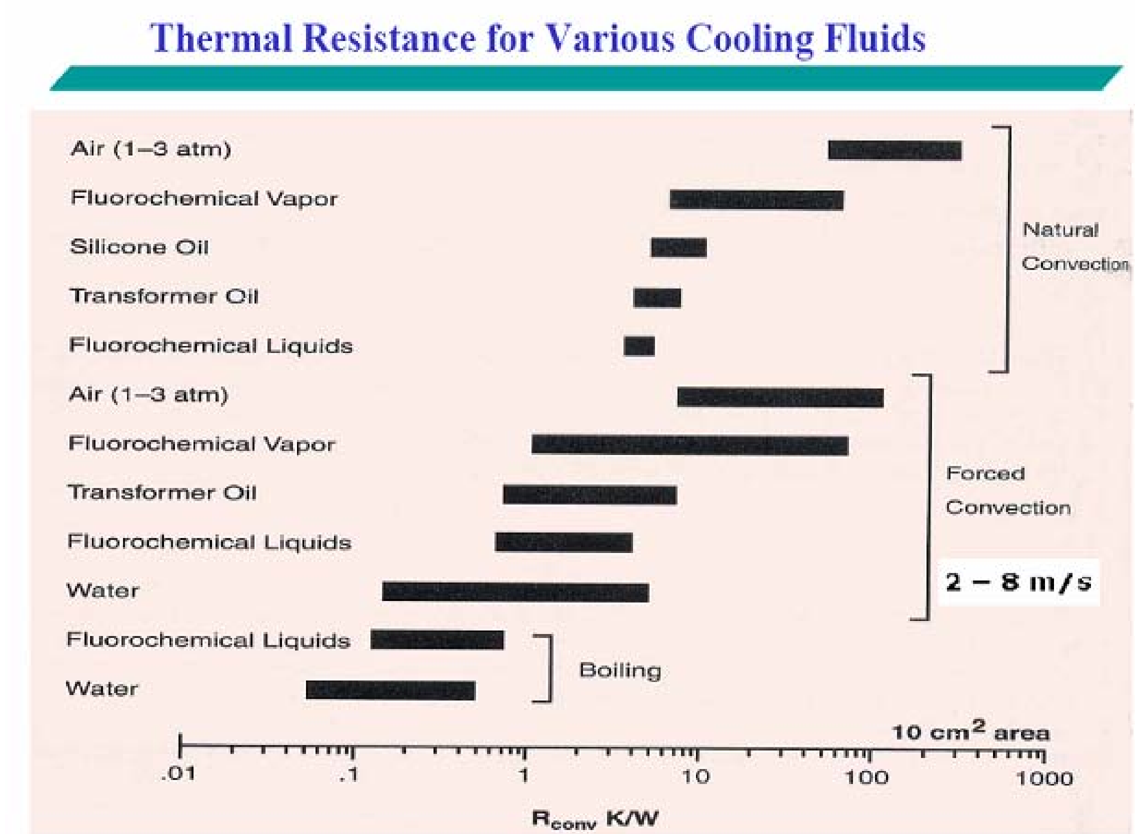
Table 3

Cooling Method	Advantages	Disadvantages
Thermoelectric coolers	• Can be used in any orientation • Small size • No moving parts • Cooling below ambient • Temperature control • Heating capability • Compatible with heat sinks, cold plates, and heat pipes	• DC power source required • Not practical for large electronic system • Cooling density of less than 10 W/cm^2
Fans and blowers	• Low cost • Installation flexibility	• Air exchange is required; potential for dust and moisture • Ineffective for high-power devices • Object cannot be cooled at or below ambient
Heat sinks	• Low cost • Installation flexibility	• No cooling at or below ambient • No temperature control
Liquid cold plates	• Size (at point of attachment)	• Cannot cool below ambient (liquid)

Cooling Method	Advantages	Disadvantages
(passive)	• Heat dissipation effectiveness	temperature • No temperature control • Potential for leaks • Liquid source availability
Heat pipes	• Reliability • Size	• Cannot cool below ambient • No temperature control
Compressor-based cooling	• Cooling large amounts of heat • Cooling below ambient • Temperature control	• Maintenance/ reliability (moving parts) • Size (units tend to be bulky) • Noise • Limited installation flexibility

Figure 1, from reference (c) shows the thermal resistance from different types of cooling fluids per 10 cm^2 area. Natural air convection provides the highest range of thermal resistance and boiling water provides the lowest range of resistance.

Figure 2



are sandwiched between ceramic plates. At the cold junction, heat is absorbed by electrons as they pass from a low-energy level in the p-type element to a higher energy level in the n-type element. A DC power supply provides the energy to move the electrons through the system. At the hot junction, energy is expelled to a heat sink as the electrons move from a high-energy element (n-type) to a lower level element (p-type). A

typical thermoelectric cooling module contains as many as 127 junctions and can pump as much as 120 W of heat. The amount of heat pumped is proportional to the amount of current flowing through the thermoelectric. Therefore, tight temperature control (<0.01°C) is possible. By reversing the current, a thermoelectric can be used to heat. This is valuable when controlling an object in changing ambient environments or cycling at different temperatures. The sizes range from 2 to 62 mm and multiple thermoelectrics can be used for greater cooling. Because of the relatively large amount of heat pumping over a small area, thermoelectrics require a heat sink and fan to dissipate the heat into the ambient environment.

For the T/R module, a thermoelectric cooling system is the most practical method for maintaining the temperature of small enclosures since it does not require fluid convection where plumbing is needed. In addition, thermoelectric system uses forced air convection, which has the thermal resistance range between 8 K/W and 100 K/W per 10 cm^2 area, from figure 1. As shown in figure 1, thermoelectric device is sandwiched between two heat sinks. One heat sink is placed into the enclosure, while the other remains outside. As current flows through the thermoelectric, the inside heat sink cools, allowing it to absorb heat from the enclosed air. A fan is used to circulate the air to reduce temperature gradients within the enclosure, which increases the efficiency of the thermoelectric device. The hot-side heat sink increases in temperature as the heat is absorbed from the enclosure as well as from the joule heat pumped into it. The ambient air absorbs the heat from the hot-side heat sink. As with the cold side, a fan on the hot side will greatly increase the performance and efficiency of the thermoelectric. The temperature of the enclosure can be controlled through simple on-off thermostats or more precise controllers that adjust the input power to the thermoelectric depending upon temperature. Condensation removal can be accomplished by using drainage ports or incorporating absorptive materials and wick structures. Consistent temperature control and cooling below ambient can improve component reliability.

IV. CONCLUSION

This Technote provides the technical reference for the cooling of the T/R module. The recommendation is to use the thermoelectric system to cool the T/R module due to its small size and temperature control capability. The advantage of the small size of thermoelectric cooler is the reduction in overall weight and size of the DARBC system, which increases overall system modularity and transportability.

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DARBC-TN-11 ELECTRONIC ATTACK

Document Type: Technical Note	**Document Number:** DARBC-TN-11
Program: DARBC	**Classification:** Unclassified

TITLE: DARBC Electronic Attack Capability

PROBLEM STATEMENT:

The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) is being designed primarily to search for, detect, and track Ballistic Missiles and counter-stealth threats, but with minor modifications to the radar's design this system could potentially be used as a "Soft Kill" weapon to counter Anti-Ship Cruise Missiles (ASCMs) and other threats. The idea is that the DARBC will be able to direct radiation in order to disrupt communication and/or destroy electronics onboard enemy platforms and weapons. This technote will discuss the potential capabilities that exist for the DARBC to be used as a weapon.

Expected output of technote: Summary of the EA capabilities the DARBC would have as designed to meet the primary missions only without specifically adding any additional components (hardware). Also, if minor hardware changes are needed to add a particular capability, those options will be discussed as well.

Prepared by: Paul Dailey	**Original Date:** 25 August, 2006	**Comments:** Final Version submitted
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Ian Barford	**Date:**	
Reviewed by: David Bedford	**Date:** 22 June, 2006	Comments made to Rev 2 of the technote.
Reviewed by: Jack Chung	**Date:** 17 August, 2006	Update Final Revision
Reviewed by: Bob Hazle	**Date:** 19 August 2006	Reviewed
Reviewed by: Stan Hill	**Date:**	
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. PURPOSE

The Digital Array Radar for Ballistic Missile Defense (BMD) and Counter-stealth (DARBC) is being designed primarily to search for, detect, and track ballistic missiles and counter-stealth threats, but with minor modifications to the radar's design this system could be used as a "Soft Kill" weapon to counter Anti-Ship Cruise Missiles (ASCMs) and other threats. The idea is that the DARBC will be able to direct radiation in order to disrupt communication and/or destroy electronics onboard enemy platforms and weapons. This technote will discuss the potential capabilities that exist for the DARBC to be used as a weapon.

II. BACKGROUND

Electronic Attack (EA) is defined as the division of Electronic Warfare (EW) involving the use of electromagnetic or directed energy to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability[132]. EA includes actions taken to prevent or reduce an enemy's effective use of the electromagnetic spectrum, such as Electronic Counter Measures (ECM) (jamming and deception) and employment of weapons that use electromagnetic, optical or directed energy as their primary destructive mechanism an in Electromagnetic Pulse (EMP) (lasers, RF weapons, particle beams) [133] . This paper will discuss both the jamming and destructive mechanisms that could be incorporated in the design of the DARBC.

III. DISCUSSION

The DARBC can be primarily classified as a AN/SPQ type radar as it is an at-sea based radar platform with missions of searching for and detecting enemy missiles, performing identification and recognition, and some level of surveillance and control. However, with no additional modifications to the physical technology, this radar could also be capable of performing other EA functions as more of an AN/SLQ (countermeasure) system. This multi-role, multi-purpose DARBC system could ultimately be classified as an AN/SSQ if all of these capabilities can be realized. Table 1 shows the Joint Electronics Type Designation System (JETDS) which describes the classification of all US military electronic equipment[134].

First Letter Platform Installation	Second Letter Equipment Type	Third Letter Function or Purpose
A - Piloted aircraft B - Underwater mobile, submarine D - Pilotless carrier F - Fixed ground G - General ground use K - Amphibious M - Mobile (ground) P - Portable S - Water T - Ground, transportable U - General utility V - Vehicular (ground)	A - Invisible light, heat radiation C - Carrier D - Radiac F - Photographic G - Telegraph or teletype I - Interphone and public address J - Electromechanical or inertial wire covered K - Telemetering L - Countermeasures M - Meteorological N - Sound in air P - Radar	B - Bombing C - Communications D - Direction finder, reconnaissance and/or surveillance E - Ejection and/or release G - Fire control or searchlight directing H - Recording and/or reproducing K - Computing M - Maintenance and/or test assemblies N - Navigation aids Q - Special or combination of purposes R - Receiving, passive detecting S - Detecting and/or range and bearing, search

W - Water surface and underwater combination Z - Piloted-pilotless airborne vehicle combination	Q - Sonar and underwater sound R - Radio S - Special or combinations of types T - Telephone (wire) V - Visual and visible light W - Armament X - Facsimile or television Y - Data Processing	T - Transmitting W - Automatic flight or remote control X - Identification and recognition Y - Surveillance and control

Table 1

The two types of EA which are used against enemy communications are jamming and deception, both of which are types of ECM. Jamming is also be thought of as "Concealment or Masking", which broadcasts lots of radiation within the frequencies used by the enemy for communication in an effort to overpower the communication signals and inhibiting the passage of the enemy messages. Deception or "Forgery" sends communication signals to the enemy radar, imitating the enemy's communications in an effort to confuse the enemy's communication systems. To do this, the DARBC would have to be able to monitor (receive) enemy communications and imitate those signals and broadcast them out back to the enemy receivers[135].

The main threats against the DARBC platform would be ASCMs. ASCMs can have various modes of guidance such as GPS, active homing, semi-active homing, heat seeking, TV or infra-red guided. In all of these cases, there has to be either communication between the ASCM and the DARBC platform (homing or heat seeking) or communication between the ASCM and another guidance source (GPS). If these communication methods can be interrupted, there is a greater potential of the ASCM missing the target.

Since the DARBC is a VHF/UHF radar and does not have the capability to communicate on other frequencies, it is not likely that the DARBC would be a very good as a deception Electronic Counter Measure (ECM) platform. ASCMs such as the Exocet use X-band active homing which is outside the range of the DARBC's spectrum[136]. Since the DARBC would not be a good candidate for conducting jamming and deception missions, we will now look at the possibility of using the DARBC as a destructive RF weapon.

Based on the radar technical parameters research, the DARBC will be capable of producing in excess of 500 kW peak of output signal. If all this power can be directed at an incoming ASCM at relatively close range (compared to the DARBC's typical search ranges), the DARBC can generate a Non-Nuclear Electro-Magnetic Pulse (NNEMP) which is generated without use of nuclear weapons[137]. In order to achieve the frequency characteristics of the pulse needed for optimal coupling into the ASCM, the addition of wave-shaping circuits and/or microwave generators need to be added between the DARBC radiating element and the antenna.

When NNEMPs are coupled with existing electronic systems such as ASCMs, damaging current and voltage surges can be induced on those systems causing failure[138]. The signals power and the pulse of the signal are what drive the effectiveness of an EMP

signal. Higher frequency signals such as microwave signals are more effective than lower frequencies[139], such as VHF or UHF. Due to the low operational frequencies, even with the high power output, the DARBC could not effectively deliver EMPs on close range targets.

IV. CONCLUSION

Even with the ability to direct high amounts of energy, the DARBC would probably not be capable of emitting EMPs effectively as part of a platform self-defense effort or short range offensive effort. Further investigation could still be conducted into the vulnerabilities of electronic systems to high power VHF and UHF signals. The DARBC would not be a good candidate for an ECM platform which could produce jamming or deception forms of EA due to the limited bandwidth of the radar. However, if enemy communications were known to be operating in the VHF or UHF spectrums, the DARBC could potentially be used to jam those communications.

DARBC-TN-12 BUDGET & LOGISTICS

Document Type: Technical Note	**Document Number:** DARBC-TN-12
Program: DARBC	**Classification:** Unclassified

TITLE: DARBC Logistics Support and Budget Requirements

PROBLEM STATEMENT:

The Digital Array Radar for Ballistics Missile Defense (BMD) and Counter-stealth (DARBC) radar system is a significant departure from current radar design concepts and requires an evaluation of supportability concepts to avoid incurring avoidable Life Cycle Costs (LCCs) and risk areas. DARBC must incorporate the essential logistics support elements in order to maintain the readiness and operational capabilities that are defined in the DARBC Initial Capabilities Document (ICD) and Capability Development Document (CDD). Logistics supportability factors are integral elements that must be consider while developing a support strategy that optimizes those functional operational requirements that must be achieved for the DARBC. In order to ensure that a viable, cost-effective support infrastructure is planned and put into place, the reliability, maintainability and availability of the DARBC radar system will have to be evaluated. This may encompass conducting trade-off studies in order to determine the most cost effective solutions are achieved and to ensure that an acceptable level of capability is available to the front-line users that is both affordable and deliverable.

Expected Outputs of Study:

1. Identification and evaluation of essential logistics support concepts and their impact to LCCs.

Prepared by: Stanley G. Hill	**Original Date:** 14 August, 2006	**Comments:** Revised 18 August, 2006
Reviewed by: Carla Bacchus	**Date:**	
Reviewed by: Ian Barford	**Date:**	
Reviewed by: David Bedford	**Date:**	
Reviewed by: Paul Dailey	**Date:** 19 August, 2006	Final Review for submission conducted.
Reviewed by: Robert Hazle	**Date:** 18-19 August, 2006	Review and comments made.
Reviewed by: Mark Mihocka	**Date:**	
Approved by: Professor Green	**Date:**	

I. Purpose:

This Technote will discuss the logistics and associated budget requirements affecting supportability that must be achieved to operationally sustain the DARBC radar system in the fleet.

II. Background:

An acquisition logistics process will have to be implemented for the DARBC radar system in order to achieve logistics program success based on the design, test, and production practices conducted during the various acquisition phases. The systems engineering process and the logistics planning must be accomplish at the same time in order to generate the logistics support requirements to maintain the DARBC radar system for its mission purposes. Operational and maintenance constraints must be identified early to ensure that the design development outcomes for the DARBC radar system can be implemented and supported at a practical cost. DARBC design concepts differ significantly from traditional radars in service today. These concepts must be assessed early for their impact and strategies developed to mitigate cost risks.

III. Discussion:

DARBC Radar System Maintenance Concepts and Supply Support Strategies

DARBC Radar System Equipment Support

The supply support strategy will be to ensure that there is an adequate range and depth of On-Board Repair Parts (OBRP) available for the fleet to properly operate and maintain the DARBC radar system. Due to the planned high design reliability for the DARBC radar system, OBRPs will not be calculated as allowance items in the ship. All supply requisitions for parts will be processed by NAVICP-M using normal operating supply procedures.

Maintenance Concepts

The DARBC radar system maintenance concept will be based on Organizational Level (O-Level) and Depot Level (D-Level) maintenance. There is not Intermediate Level Maintenance planned for the system unless required for DARBC unique requirements for alignment calibration discussed below and in the Technote on ship flexure. The use of prototype systems and modeling of spaces will be used to evaluate maintenance concepts and identify risk areas such as access to compartments and spaces where radar elements are placed.

Organizational Level Maintenance

O-level maintenance will include Preventive Maintenance (PM) and Corrective Maintenance (CM). An Electronic Technician (ET) will accomplish O-Level maintenance. O-Level Corrective Maintenance will use failure diagnosis, Built-in-Tests (BIT) and reach-back distance support services that will provide the ET significant technical expertise resources. Prognostics will be used by off-ship resources to monitor system status relieving O-Level support of system monitoring functions and performing scheduled maintenance that can be performed remotely. Maintenance will be limited to removal and replacement of failed parts at the Lowest Replaceable Units (LRUs).

Preventive Maintenance

Preventative Maintenance **(**PM) will be accomplished and conducted using the ship's 3M Planned Maintenance System (PMS). PM will be performed using procedures documented in Maintenance Index Pages (MIPs) and Maintenance Requirement Cards (MRCs). Preventive and Planned maintenance will be performed by an ET and significantly augmented by remote distance support using prognostics to evaluate system performance and identify parts that require replacement reducing on-ship manpower required for maintenance.

Corrective Maintenance

Corrective Maintenance restores equipment to operational condition. It will be limited to identification and replacement of failed LRUs such as Circuit Card Assemblies (CCAs). Faults identified during planned maintenance actions or equipment operations will be isolated to a specific LRU through the use of BIT trouble shooting techniques. Corrective maintenance will be performed by an ET through a mix of repair piece parts repair and LRU replacement. A design goal is to isolate faults to a single LRU 95% of the time. This design goal will be assessed against the impact of adding additional parts and ETs to meet supportability goals. The identification of failed items using remote diagnostics will require fault diagnosis to a higher level of certainty.

Depot Level Maintenance

Depot Level will consist of repairing failed assemblies, subassemblies and modules turned in by the using ship. The Allowance Parts List (APL) and the Master Repairable Items List (MRIL) will identify those items in the DARBC radar system designated as depot level repairable items.

During the ships scheduled overhaul periods (Regular Overhaul (ROH)) the DARBC radar system static/dynamic ship alignment of the entire array of elements will be performed by the Original Equipment Manufacturer (OEM), overhaul shipyard or Navy approved organic depot. The dispersion of array elements across the entire ship superstructure and tolerances required for Ballistic Missile Defense (BMD) will make the

radar susceptible to performance degradation due to ship flexure. Periodic alignment and calibration may be required beyond that normally conducted on today's in service sensors. Evaluations of different concepts for alignment are discussed in Technote on ship flexure. These include pierside beacons, shore facility beacon and electronic target generators, and embedded self measurement and corrective systems. This may require an additional level of maintenance beyond just O and D level.

Technical Assistance

Direct Fleet support will consist of resolution of maintenance/repair problems which are beyond the capability of ship personnel to correct. Request for Fleet support in the resolution or repair of the DARBC radar system casualty will be coordinated by the applicable Type Commanders (TYCOMs) with the local Regional Maintenance Centers (RMCs).

Direct Fleet support can be reduced for the DARBC radar system by implementing BIT technology in the design of the DARBC radar system. BIT technology can be utilized on the DARBC radar system for two reasons: (1) BIT lends itself to automated long distance support and (2) onboard trouble shooting assistance to the technician. The long distance support can be comprised of many shore based facilities including the Depot, Intermediate or In Service Engineering Agent (ISEA). This long distance support can be utilized via secure internet, teleconferencing or even telephone. Utilizing BIT technology and long distance support will reduce Mean Time to Repair (MTTR), manning requirements and increase Operational Availability (A_o). Distance support can also employ prognostics to assess system trends in performance and determine where parts may be ready for failure and replacement. The repair part can be shipped and installed before system failure and downtime result.

Supply Support Strategies

The supply support strategy is to ensure there is an adequate range and depth of ORBPs available for the Fleet to properly operate and maintain the DARBC radar system. The DARBC radar system key performance parameters for reliability, maintainability, and availability are defined to be medium-to-high, and therefore ORBPs will not be calculated as allowance items in the ships load out Coordinated Shipboard Allowance List (COSAL). All requisitions for parts will be processed by NAVICP-M using normal operating supply procedures. The required parts for the DARBC radar system will be provision by the ISEA and management in the applicable APLs by NAVICP-M. Spare parts shall be requisitioned using procedures described in NAVSUP P-485 Afloat Supply Procedures. Standard and non-standard requisitioning procedures apply.

DARBC Radar System Manpower, Personnel and Training

The DARBC radar system training and manning requirements will be documented by developing a Navy Training System Plan (NTSP). The NTSP will be promulgated and reviewed by a future sponsor, Fleet, training communities, Director of Navy Training and Navy Manpower Analysis Center. The future sponsor approves the NTSP which will establish the baseline for training and manning requirements that the DARBC radar system must comply to meet the fleet readiness requirements. The DARBC radar system key performance parameters for reliability, maintainability, and availability are critical during the design phase to identify drivers of support and manpower requirements. The maintenance task times, maintenance skill levels and number of maintenance personnel required will be determined by the following metrics:

- Reliability (MTBF key performance parameters)
- Maintainability (MTTR, maintenance task times)
- Availability (Task time limits).
- Reliability and Maintainability tests.
- Performance monitoring/fault detection/fault isolation and diagnostics.
- Test conducted under representative operating conditions.

Based on the key performance parameters to be achieved and meeting the Navy's new concept for fewer personnel to operate an entire ship, the manning requirements for the radar system aboard ship should be one technician that will have collateral duties as a maintainer and operator.

DARBC Radar System Packaging, Handling, Storage and Transpiration

The goal of Packaging, Handling, Storage and Transportation (PHS&T) is to ensure to the fleet user of the DARBC radar system when and where it is needed, with factory built-in reliability unimpaired. MIL-E-17555 sets forth packaging requirements for electronic equipment, MIL-STD-794 sets forth general procedures for packaging and packing, and Naval Material Command Instruction (NAVMAINST) 4030.11A sets forth policy concerning requirements for packing hazardous material. The OEM must adhere to the above standards in order to deliver a functional DARBC radar system to the fleet.

DARBC Radar System Configuration Management

The Configuration Management (CM) process will be used to evaluate and approve/disapprove proposed design changes that will affect the DARBC system form, fit or function that is defined in the ICD and CDD. These changes are referred to as Class I changes. This process will ensure that configuration control is maintained throughout the life cycle of the DARBC, and that all logistics documentation is current and available to the fleet for operational support.

DARBC Radar System Technical Data

Technical Data Packages

Technical data for the DARBC radar system will include commercial manuals, provision technical data, commercial drawings, MIPs, and MRCs.

Technical Manuals

NAVSEAINST 4160.3A establishes the policy, responsibilities, and requirements for the planning, budgeting, development, distribution, and life cycle management of NAVSEA Technical Manuals (TMs)/Interactive Electronic Technical Manuals (IETMs). The DARBC radar system must comply with all requirements set forth in the NAVSEAINST in order to provide useable and accurate technical manuals to the fleet.

Planned Maintenance System Documentation

Planned Maintenance System (PMS) tasks are conducted using the ship's 3-M PMS. The DARBC radar system PMS will be performed using procedures documented in the MIPs and MRCs.

Provisioning Technical Documentation (PTD)

The ISEA for the DARBC radar system will be responsible for process Provisioning Technical Documentation (PTD). All ISEA reviewed PTD changes will be forwarded to NAVICP-M for revision of the DARBC radar system APLs.

Drawings

Commercial drawings from the OEM will be utilized in order to produce Navy standard Installation Control Drawings (ICDs) for applicable ship classes in which the DARBC radar system will be installed.

Budget Requirements

As noted in the DARBC CDD program costs and projections of LCCs are outside the scope of this capstone project. However specific systems attributes have been identified by capstone team members to be key cost driver risk areas that must be address at the earliest stages of the acquisition cycle in order to determine if trade offs in performance requirements may be necessary in order to meet the criticality of the mission that the DARBC radar system must perform. The key anticipated cost driver risk areas that have been identified for the DARBC radar system are manning, reliability, maintainability, dynamic radar-ship alignment and static radar-ship alignment or calibration.

Identification of the lowest Work Breakdown Structure (WBS) levels must be acknowledged in order to distinguish risk events associated to the DARBC radar system. The WBS levels will be determined by using cost risk modeling software that includes a Monte Carlo Simulation to obtain a program level probability distribution. The cost risk assessment modeling results will be utilized to determine actual risk cost overruns and to identify new risk drivers if applicable. When possible the capstone team should compared in use radar systems cost risk data to the DARBC radar system to assist in the identification of what cost risk drivers and software modeling will be required to effectively identify/compute cost risk drivers. It should be noted that specific, relevant cost risk information used to developed other radar programs is very difficult to obtain because, once a radar system is fielded, the records related to the project are either archived or dispersed among the project participants.

Logistics Risk Metric Assessments

Logistics risk metrics were performed for the DARBC radar system based on the key cost driver risk areas that were identified in the DARBC CDD. The logistics risk metrics will be utilized to determine risk handling priorities, execute risk handling plans, observed the status of risk handling actions, determine and acquire the resources necessary to execute risk management strategies. To analyze the cost driver risk areas logistics risk metric tables were created to measure and rate program activities associated with specific critical logistics elements noted as Manpower and Personnel, Design Interface and Support Equipment.

Table 1.0 represents logistics risk metric rating values that has been assigned based on practical knowledge and experience. The numerical rating value (1) represents little or no program fulfillment with the completed metric or progress to completing the metric, (3) for minimum fulfillment, (5) for significant fulfillment and Not Applicable (N/A) if that metric is not applicable at the time of the assessment.

Rating vs. Risk Conversion Table 1.0

Rating Values	Risk Assessment
2.0 to 2.2	**High (Red)**
2.3 to 3.7	**Moderate (Yellow)**
3.8 to 5.0	**Low (Green)**
N/A	**Blank**

Table 2.0 represents the Manpower and Personnel metrics requirements that will aid in understanding how to handle a potential cost risk problem. This risk metric will aid in determining the needs for military manning with proper skills and grades required to operate, maintain and support the DARBC radar system over its lifetime at peacetime and

wartime rates. The Manpower and Personnel program activity rating received an overall risk assessment of moderate. This program activity rating could change if another cohort continues to work on this capstone project where cohort #4 stops based on risk metrics receiving better rating values with respect to more information being available for review.

Manpower and Personnel Table 2.0		
Program Activity	**Metrics**	**Rating**
1. Maintenance Concept/Plan – includes identification of the frequency of failures for maintenance, maintenance task times, maintenance skill levels and number of maintenance personnel required. These factors are critical during the design phase to identify drivers of support and manpower requirements.	1.1 Identifies requirements for: ˜ Special skills. ˜ Maintenance and operator labor hours by rate by year. ˜ Number of personnel by rate by maintenance level by year.	**2.5**
	1.2 Identifies requirements for manpower factors that impact system design utilization rates, pilot-to-seat ratios and maintenance ratios.	**2.0**
	1.3 Maintenance task times, maintenance skill levels and number of maintenance personnel required have been derived from the following: ˜ Reliability (e.g., MTBF). ˜ Maintainability (e.g., MTTR, maintenance task times). ˜ Availability (e.g., task time limits). ˜ Reliability and maintainability tests. ˜ Performance monitoring/fault detection/fault isolation and diagnostics. ˜ Test conducted under representative operating conditions.	**3.7**
	Activity (8.2/3)	**2.7**

Table 3.0 represents the Design Interface for reliability, maintainability, quality and availability metrics requirements that will aid in understanding how to handle a potential cost risk problem. This risk metric will aid in determining systems engineering activities in which the DARBC radar system most perform to that impacts supportability concerns. Many of the metrics received a score of 1 based on little information is available at this stage and scope for this project. This program activity rating received an overall risk assessment of high. The program activity rating could change if another cohort continues to work on this capstone project where cohort #4 stops based on risk metrics receiving better rating values with respect to more information being available for review.

Design Interface (Reliability, Maintainability, Quality and Availability) Table 3.0		
Program Activity	**Metrics**	**Rating**
2.0 Reliability, Maintainability, Quality and Availability – are requirements imposed or analyses performed to insure that the system is operationally ready for use when needed, will successfully perform assigned functions, and can be operated and maintained within the scope of the logistics concept and plan.	2.1 The following measures of effectiveness or equivalent are identified in measurable quantifiable terms based on similar systems and available detail design information: Availability. Mean Time Between Failures (MTBF). Mean Time To Repair (MTTR). Frequency and duration of preventive or scheduled maintenance. Battle damage repair capability. Readiness thresholds for all system downtime, including scheduled maintenance. 2.2 Reliability, maintainability and availability of the system are continually assessed through analyses and testing to ensure life cycle objectives will be met. 2.3 Design and layout minimizes unnecessary removal of items to gain access for maintenance and minimizes design of special tools. 2.4 Maintainability predictions and task time analyses are completed for organizational level or shipboard maintenance as a minimum. 2.5 Mock-ups, prototypes and/or simulations to assess accessibility are completed as part of design. 2.6 Accessibility and maintainability are validated through tests. 2.7 A quality program is established to assure implementation of design requirements into process control characteristics.	**3.7** **1.0** **1.0** **4.0** **1.0** **1.0** **1.0**
	Activity(12.7/7)	**1.8**

Table 4.0 represents the Dynamic/Static Radar-Ship Alignment or Calibration metrics requirements that will aid in understanding how to handle a potential cost risk problem. This risk metric will aid in determining maintenance and repair planning requirements for the DARBC radar system antenna elements that impacts supportability concerns. Many of the metrics received a score of 1 based on little information is available at this stage and scope for this project. This program activity rating received an overall risk assessment of high. The program activity rating could change if another cohort continues to work on this capstone project where cohort #4 stops based on risk metrics receiving better rating values with respect to more information being available for review.

Dynamic/Static Radar-Ship Alignment or Calibration Table 4.0		
Program Activity	**Metrics**	**Rating**
3.0 Maintenance Plan to repair or calibrate antenna elements – includes documentation of the Support Equipment (SE) concept as a result of the level of repair analysis, organic repair/contractor (OEM) support and the sparing concept.	3.1 Establishes the diagnostics concept to test the antenna elements. 3.2 Identifies test and fault isolation capabilities desired of automatic, semi-automatic and manual test equipment at all maintenance levels, expressed in terms of realistic and affordable probabilities and confidence levels to repair or calibrate antenna elements. 3.3 Identifies the SE associated with the most economical level of repair (usually determined in the level of repair analysis) unless over-ridden because of non-economic factors. 3.4 Identifies manpower, training and maintenance task requirements. 3.5 Identifies required technical documentation to support the SE. 3.6 Identifies the level of maintenance at which the various SE is required to repair or calibrate antenna elements (e.g., organizational, intermediate and depot level maintenance). 3.7 Types and quantity of SE for each location has been established. 3.8 Calibration requirements are specified. 3.9 Support Equipment Requirements Document is submitted by the contractor to justify SE requirements and initiate follow-on support activities.	**1.0** **1.0** **1.0** **1.0** **1.0** **1.0** **1.0** **1.0** **1.0**
	Activity(9/9)	**1.0**

IV. Conclusion:

DARBC radar system logistics support elements and cost risk drivers metrics were identified to ensure the operational and the support characteristics for the radar will be achieved to perform its assigned mission effectively and efficiently over a operationally life-cycle time period. A supportability strategy was identified which explains the levels of support required to sustain the DARBC radar system in the fleet and meet mission requirements. Cost risk based modeling was discuss as a requirement to estimate and management the cost for the DARBC radar system plus the need for a methodology to better estimate the cost of other systems attributes drivers that have been identified as potential risks drivers. The cost risk model must also provide risks and uncertainty methods to structure a project cost estimate to produce a “range of probable

cost" and include explicit identification of high-cost and schedule risk drivers, leading to an ability to develop explicit risk management plans for the DARBC's development process.

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